THE UNIVERSITY OF ALBERTA

THE EFFECT OF TURBULENCE ON CURRENT METERS

by

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ABSTRACT

The effects of turbulence on current meters are reviewed. The calibration curves determined in still water and in water with artificially induced turbulence are compared for a screw-type meter. The effect of blade pitch and proximity to boundaries is investigated.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor J. B. Nuttall for his guidance and constructive criticism throughout this investigation. To Mr. C. R. Neill for his translations of the foreign publications; to Professor A. W. Peterson and the staff of the Hydraulics Laboratory for their valuable help in setting up and revamping equipment; the author is truly grateful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER I - INTRODUCTION

1.1 THE PROBLEM

The basic reason for this work was that research in the subject, over the years, seems to have produced no quantitative information on the likely errors of discharge observations due to rating current meters in still water and then using them in turbulent water. While five percent errors in current meter observations are tolerable for irrigation canals provided everyone accepts them, and errors of ten percent are unlikely to matter in river measurements, there are special cases that demand accuracy down to one percent or better if possible. For example, if channel seepage losses are to be determined by differences of discharges, an error of one percent at one end due to excessive turbulence there might cause fifty percent errors in the estimate of the seepage.

A number of attempts have been made to simulate the components of turbulence by oscillating the meter vertically and parallel to the flow, and to simulate the obliquity of the flow striking the meter by turning the meter at various angles to the flow. These are not very convincing quantitatively.

This testing program was initiated to try to relate the errors in meter observations with the turbulence present in the flow and to find the errors introduced by using still water calibration curves for determining flows in turbulent water. It is the hope of the University to carry out a continuing program on this subject of which this study will be the first phase.

1.2 FEATURES OF CURRENT METERS

Hydrometric current meters are divided into two main groups:

(1) Cup current meters which have a bucket wheel rotating about a vertical axis; the Price current meter being the most common of this type.

(2) Vane current meters having a rotor axis coinciding with the direction of flow, which, depending on the rotor shape, are also divided into:

   (a) spoke-vane current meters, consisting of a rotor with several blades connected to the boss by means of spokes;

   (b) helical (screw or propeller) current meters with a rotor consisting of several screw blades.

The use of the Price meter is confined mostly to English-speaking countries being more robust and easily used in unskilled hands. It is sometimes referred to as the Gurley meter. In Europe the Ott, Amsler and Stoppani are generally favored, being vane current meters; in America the names associated with this type are the Haskell, Hoff and Fteley-Stearns.

The current meter used throughout this investigation was a helical current meter manufactured by A. Ott, Kempton, Bavaria, for laboratory use. Plate 1 shows a picture of the meter while Plate 2 shows the three types of propellers used in this study. The meter was supported in all the tests by a rod. In practice the current meters are usually suspended on cables allowing the meter to move a small amount sideways and backwards. This introduces additional errors to those of the

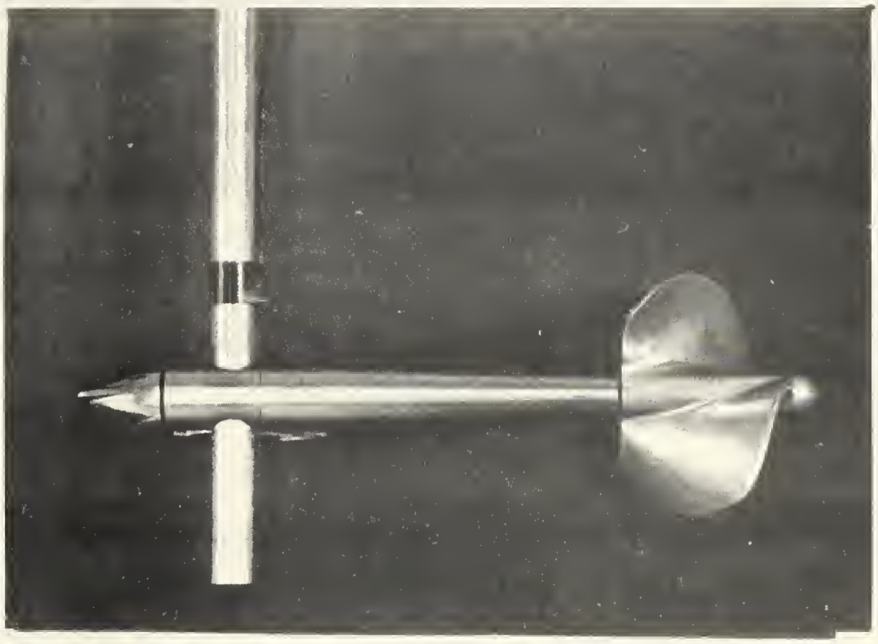

Plate 1 - Ott Laboratory Type Current Meter

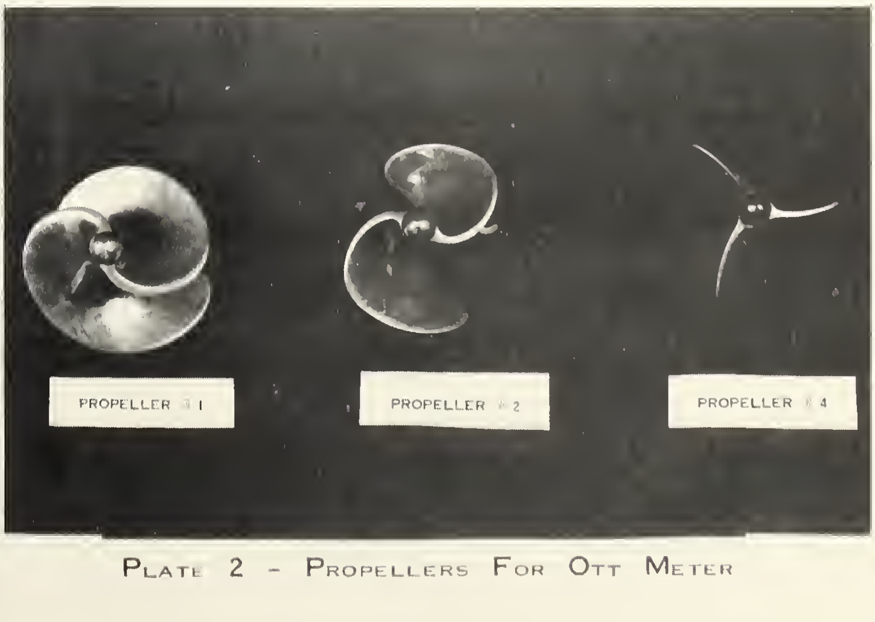

Plate 2 - Propellers For Ott Meter

turbulent fluctuations and may or may not be compensated for by the meter being able to move in a horizontal plane, thereby remaining parallel to the flow at all times.

The lack of a Pygmy Price meter at the time this study was begun made it necessary to use the available Ott meter for this study. It is the intention of the University to carry out similar experiments using the recently purchased Pygmy Price meter.

1.3 NOTATION

The following notation is used throughout:

U = instantaneous velocity in the direction of flow.

$\overline{U}$ = mean velocity of the water in the direction of flow.

u' = the fluctuation in the velocity from the mean velocity in the direction of flow.

v' = the fluctuation in velocity y direction.

w' = the fluctuation in velocity in the z direction.

d = depth of flow.

b = breadth of the flume.

V_T = velocity at which meter is towed, positive if in upstream direction.

V_W = velocity at which water is flowing along the "line of tow" and at the meter depth.

V_n = water velocity which is represented by the revolutions recorded from the meter propeller.

c.f.s. = cubic feet per second.

mm./sec. = millimeters per second.

N = revolutions of meter propeller per second.

m. = meters.

ft. = feet.

CHAPTER II - THEORETICAL BACKGROUND

This section is devoted mainly to those aspects of turbulence that refer to the measurements of flow in turbulent waters. No attempt is made to go deeply into the various theories of turbulence as these may be found in test-books dealing with the subject.

2.1 TURBULENCE

"Turbulent Fluid Motion", as defined by Hinze (Ref. 1), "is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned."

Isotropic turbulence occurs when its statistical features have no preference for any direction, so that perfect disorder reigns (mean velocity has no gradient). Non-Isotropic turbulence, or sometimes called shear-flow turbulence, has a velocity gradient and is the type we are dealing with here.

If the fluctuating quantities have the same mean values in all parts of the fluid flow it is said to be homogeneous.

2.2 THEORY

2.2.1 Intensity and Degree of Turbulence.

The basic characteristic of turbulent motion is that while the momentary velocity components appear to fluctuate in a haphazard manner, the average velocity over a sufficiently lengthy period of time remains constant. Thus at each and every point there is a certain average velocity, representing the statistical result of inordinate changes, which is constant in size and direction.

If the mean velocity in the direction of flow is denoted by $\overline{U}$ with the condition that:

$$\overline{U} = \frac{1}{t}\int_{o}^{t} U \, dt$$

where U is the instantaneous velocity and t a sufficiently long period of time, then $\overline{U}$ is constant. The instantaneous velocity will therefore consist of $\overline{U}$ plus vectorily (u', v', w') the fluctuation in the velocity in the x, y and z direction, respectively. By definition the time average of these fluctuations must be zero; that is:

$$\int^{t} u' dt = 0; \quad \int^{t} v' dt = 0; \quad \int^{t} w' dt = 0$$

Dryden and Kuethe, in 1930, introduced the following definition to define the violence or intensity of the turbulence fluctuations:

$$u = \sqrt{\overline{u'^2}} \; ; \quad v = \sqrt{\overline{v'^2}} \; ; \quad w = \sqrt{\overline{w'^2}}$$

They also defined the relative intensity or degree of turbulence by the ratio of the root mean square value u, of the longitudinal velocity component, to the mean velocity $\overline{U}$, or symbolically:

$$\frac{u}{\overline{U}}$$

There is some controversy as to the validity of this as a measure of the turbulence. This is used as a measure of turbulence for this study. References 2 and 3 discuss this further.

2.2.2 Scale of Turbulence

To describe turbulence quantitatively, another parameter must be introduced to represent the masses of water having

individual behavior; their size being dependent on the dimensions of the apparatus and the flow within it. By studying oscillograms of quantities varying turbulently, a distinct pattern is seen to be repeated throughout them. These patterns are also found to be repeated more or less in space. The size of the patterns or eddies are defined in terms of correlations between velocity components at two points in space at the same time and at two different times at the same point.

Consider the fluctuations $u'_{(y)}$ and $u'_{(y+\Delta y)}$ at two points having coordinates (y) and (y +Δy) respectively. If these points are close together the fluctuations will be closely correlated. If they are far apart in comparison to the scale of the turbulence, this coefficient of correlation between $u'_{(y)}$ and $u'_{(y+\Delta y)}$ should disappear. The coefficient of correlation between the two turbulent velocities is

$$R_y = \frac{\overline{u'_{(y)} \cdot u'_{(y+\Delta y)}}}{\sqrt{\overline{u'^{2}_{(y)}} \cdot \overline{u'^{2}_{(y+\Delta y)}}}}$$

where Δy is the distance between points, the axis of y being along a line joining the two points. The over-score denotes the average values.

Generally it is assumed that the value $\overline{u'^{2}_{(y)}}$ is equal to $\overline{u'^{2}_{(y+\Delta y)}}$; R_y may then be given by

$$R_y = \frac{\overline{u'_{(y)} \cdot u'_{(y+\Delta y)}}}{\overline{u'^{2}_{(y)}}}$$

The time scale is determined by considering the correlation between the values of a fluctuating quantity at a fixed

point in the flow at two different instants t' and $t' + \Delta t$ having the respective turbulent velocities $u'_{(t)}$ and $u'_{(t + \Delta t)}$. The time scale or Eulerian Correlation Coefficient is then defined by

$$R_{e(t)} = \frac{\overline{u'_{(t)} \cdot u'_{(t + \Delta t)}}}{\overline{u'^{2}_{(t)}}}$$

The u' values and coordinates of the points may be found using hot-film anemometers, the usual method being to fix one element and travers a second sensing element perpendicular to the stream-flow in the y direction. From the observations taken the two correlation coefficients may be plotted versus their variable (y,t) and time and space scale determined from these. References 1 and 2 have extensive write-ups on the calculation of these scales.

2.3 EFFECTS OF TURBULENCE ON CURRENT METERS

When current meters are used in turbulent flows the rapidly varying velocity components present cause different parts of the rotating element to be acted upon by different influences. If the axis of rotation of the eddies, whirls and vortices present in the flow should coincide with the axis of rotation of the rotating element, an acceleration or deceleration will be temporarily applied to the element. The speed at which the rotating element can adapt itself to these influences will be dependent upon its inertia.

When current meters are rated in still water and then used in turbulent flows, the action of the water on the meter differs from that of the stream line flow encountered in rating,

in that, (a) there is an incessant change in velocity of the water coming in contact with the propeller; (b) the direction of the velocity is constantly changing, striking the propeller at an oblique angle; (c) the obliquity of the current coming in contact with the propeller may vary rapidly in direction; and (d) the distribution of the small filaments of velocity over the plane of the meter may not be uniform.

By rating current meters in flows of similar intensities and scales of turbulence as those in which the meter is to be used, all of the above differences, with the exception of (d), may be eliminated. It is possible that this difference in the velocity distribution is insignificant since the main action of the meter will be due to the mean velocity $\overline{U}$.

2.4 MEASUREMENT OF TURBULENCE

Two methods are available by which turbulence can be measured. One uses a sensing element which is placed directly into the flowing fluid and the ~~turbulence~~ turbulent qualities are measured by the changes in the mechanical, physical, or chemical properties of the sensing element. The other uses a tracer or indicator that is injected into the fluid to make the flow pattern visible; this is observed by a suitable detecting apparatus outside the field of flow.

The first method was initially developed in measuring the turbulence present in wind tunnels. It used a thin wire as its sensing element and was called a hot-film anemometer. Reference 1 gives an excellent description of its use and the corrections which have to be applied to the results. More recently, Ling and Hubbard (Ref. 4), developed the hot-film anemometer for

turbulent measurements in fluids. This uses the same principle as the hot-wire anemometer but has a sensing element of a thin metal film fused to the surface of a wedge-shaped, dielectric body. This method is the only one available by which both the intensity and scale of turbulence can be measured. This is certainly the most convenient method as the root mean square quantities and the correlation coefficients can be measured directly on meters by using suitable electrical circuits.

In the second method the movement of a bubble or drop injected into the flow is traced by recording its path on photographic film in the form of a streak. This method has been used successfully in a number of cases to determine the intensity of the turbulence but only on small models (see Appendix A for write-up and references).

Practically, there is no way of determining the turbulence present under field conditions. The hot-film anemometer could likely be adapted for field use but to date nothing has been developed. Blench (Ref. 5) suggests that experiments in current meter errors be conducted with a view to using the meter as a measure of turbulence. This would be advantageous, if possible, since both the velocity and the turbulence could be obtained at the same time. Even if an additional instrument was necessary, if it could be attached directly to the current meter in a manner so that it did not disturb the flow appreciably, it would be of great use.

CHAPTER III - LITERATURE REVIEW

The material in this chapter deals with meters in general rather than screw-type meters. Only those publications are reviewed which were felt to be of major importance or give a good coverage of the work carried out up to their time. Kolupaila (Ref. 6) has an extensive bibliography in his book for those interested in knowing the complete history back as far as the 1870's.

3.1 HISTORICAL REVIEW OF RESEARCH ON CURRENT METERS

All the work described herein was performed in the United States with the exception of Reference 9, the only foreign language source reviewed, which was carried out in France.

3.1.1 Yarnell and Nagler[(7)] in 1929 conducted the first research of any importance on this subject and are widely referred to in later publications by other authors.

In contrast to previous studies, they carried out their tests in a controlled stream of water and made a qualitative study on eleven different meters.

Their first series of tests consisted of creating artificial turbulence by inserting various obstructions or baffles into the flow and comparing the readings obtained to those in the same flow without the obstructions.

The effects of fluctuating flows and the angle of incidence of the stream filaments striking the propeller were studied by

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Note: Superscripted key numbers [(7)] refer to list of References.

artificially changing the speed of the water relative to the meter. A cam was used to produce horizontal and vertical oscillations and the meter turned at various angles to the flow. The velocity of the water was varied from 1 to 5 feet per second.

Their results indicated that turbulence may change the readings of current meters noticeably, this being caused by the obliquity of the flow and not to any noticeable degree by the unsteadiness of flow. They found that turbulence caused cup meters to over-register and the screw-type to under-register.

Included in this article is an extensive bibliography of published references on current meter characteristics up to that time.

3.1.2 Nagler[(8)] (1935) described the method of flow determination by current meter and gives the comparisons between that method and others. A description is given of the techniques of flow determination under varying field conditions and the effects of the conditions on meter observations.

He states that a few attempts have been made to discover the difference between still-water ratings and performance in flowing water by towing the meter with and against a steady current. These showed that at ordinary velocities the still-water rating gave no different result from that obtained in mildly flowing water. They admitted that these tests were only carried out on well-behaved waters with a mild current. Therefore, the still-water ratings would only apply in practice under ideal conditions of flow.

3.1.3 Chaix[9] writes of the comparative tests carried out both in the field and laboratory by the Charmilles Engineering Works between 1956 and 1960. They separated the two components of turbulence by oscillating the meters both vertically and axially in a controlled stream. Three meters were tested: an Ott Type A, a three-bladed propeller type, and a component Type F, Ott Meter.

The components produced artificially were superimposed upon the components present in the flow as the turbulence could not be measured in the field or laboratory.

He concluded that the errors in terms of turbulent intensities have the same trend as the response curves in terms of angles of incidence found in still water, this similitude being only qualitative.

For the three types of meters tested, the axial oscillations caused errors of excess and he introduced a dimensionless parameter to group the frequency of the fluctuations with the inertia of the meter. He also recognized the fact that the calibrating of a meter in still water is not sufficient when the meter will be used in turbulent flows.

3.1.4 Oltman[10] (1954) carried out a series of field tests at natural stream sites to determine the accuracy of the Price current meter in measuring velocities adjacent to the boundary and free surface. These experiments were to extend the previous work done by Pierce (Ref. 11) in 1936, which had been the basis for correcting observed velocities up till then.

The velocity measured by the current meter at a point was compared with that obtained by a pitot static tube, the pitot reading taken as being the true velocity. The tests were

carried out on two Price meters: the Type AA and Pygmy; the pygmy meter being similar to the Type AA except two-fifths of its size. The depth of flow for the majority of the test was approximately 1.5 feet.

The results indicated that Type AA meter under-registers in the order of three percent when remote from surface or boundaries, increasing as the boundaries and surface are approached. The Pygmy Price meter readings showed that they could be higher or lower than those obtained by pitot tube.

3.1.5 <u>Townsend and Blust</u>[12] (1959) simultaneously measured current velocities using cup and propeller type current meters in the lower Niagara River. They concluded that the two types give identical results where flow is non-turbulent.

In turbulent waters they found that the Price meter tends to over-register. They admit that the turbulence in the latter test was greater than that which would be present at any stream metering section.

3.1.6 <u>Kolupaila</u>[13] (1957) reviews the use of current meters in turbulent channels. He states that the cup meter is not sensitive to the direction of flow, reacting only to the maximum velocity while the screw type is intended to measure the projection of the velocity on its axis according to the cosine law. However the measured projection of the oblique velocity is usually less than the correct projection $U \cos \theta$ resulting in the screw type under-estimating the velocity when stream filaments are not parallel. He also discusses the so-called "component runner" for the Ott Current Meter and its oblique rating. He shows that this propeller coincides very satis-

factorily with the cosine law, and because of this was given the name "component runner".

3.2 SUMMARY OF PREVIOUS RESEARCH

The general conclusions which have been drawn from previous research are as follows:

1. Cup-type meters tend to over-register in waters which are highly turbulent; the magnitude of this error ranging from 5 to 10 percent (Ref. 7, 8, 12).

2. Screw-type meters under-register in turbulent waters but to a lesser degree than cup-type over-register (Ref. 7, 13).

3. The over and under registration of the meters is due mainly to the incessant changing in direction of the flow while fluctuations in the magnitude of the velocity are considerably damped by the inertia and continuity of flow (Ref. 9, 13, 14).

4. The error in registration of the meter is dependent on the position of the meter with reference to the boundaries of the channel and to the surface (Ref. 7, 10).

The lack of any quantitative information as to the magnitude of the errors involved in velocity measurements can be credited to the fact that no method is devised for determining the index of the relative degree of turbulence. There was also the problem that the meter readings in practice can only be checked against discharge measurements and it is only by performing a large number of experiments that an estimate of the average error can be reached.

CHAPTER IV - TESTING AT UNIVERSITY OF ALBERTA

This chapter covers the experimental apparatus, testing procedure and analysis of the results for all the testing performed in this investigation.

4.1 EXPERIMENTAL APPARATUS

The investigation was carried out using the towing tank in the Graduate Hydraulics Laboratory at the University of Alberta. A considerable number of modifications were made to the existing towing apparatus in order to facilitate recording of the towing speed, current meter output, and to improve the accuracy of these quantities.

The flume was 120 feet long, 3 feet wide, and 2.5 feet deep, of wood construction with fibre glass coating on the inside to ensure water tightness. Screw Jacks located every 20 feet allowed the slope to be changed from 0 to 0.63 percent. At the inlet, baffles were installed to obtain a uniform velocity distribution across the width of the flume. An adjustable tailgate allowed the depth to be regulated as necessary. Plates 3 and 4 give general views of the flume while Figure 1 outlines the details.

The tow rail, as shown in the plates and figures given above, was fixed. The towing carriage was supported by nylon wheels riding inside the rail. It was pulled by cables running the full length of the rail and connected to a 1/4 horsepower motor having a variable gear box. This allowed speeds up to 10 feet per second to be obtained. Details of the rail and dolly

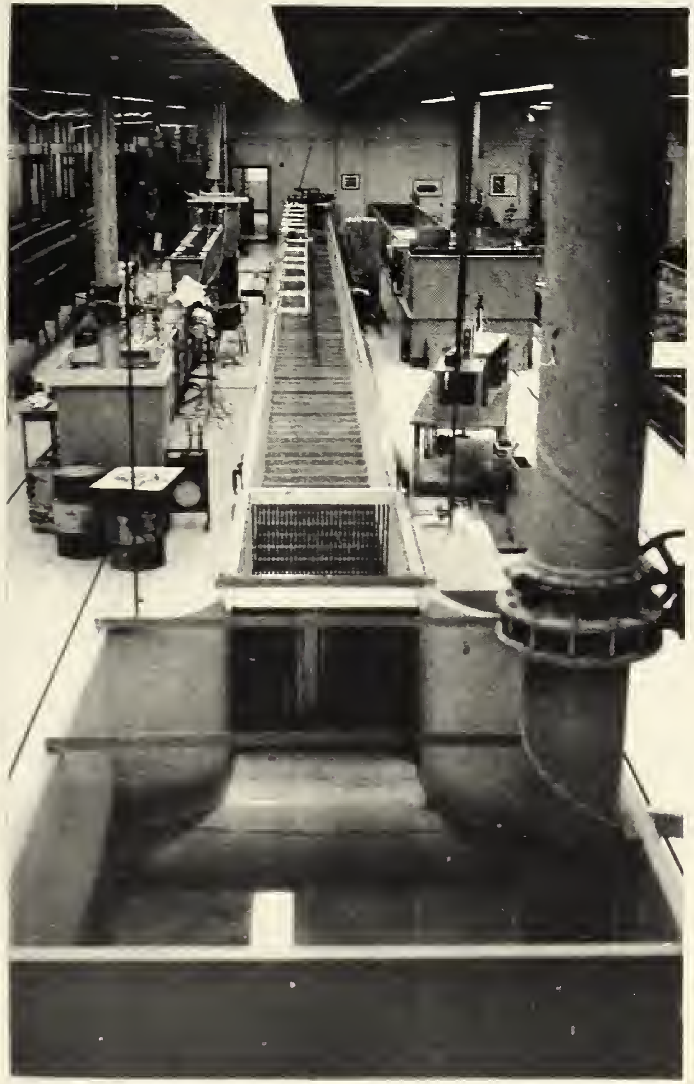


Plate 3 - View of Flume With Rough Bed in Place.

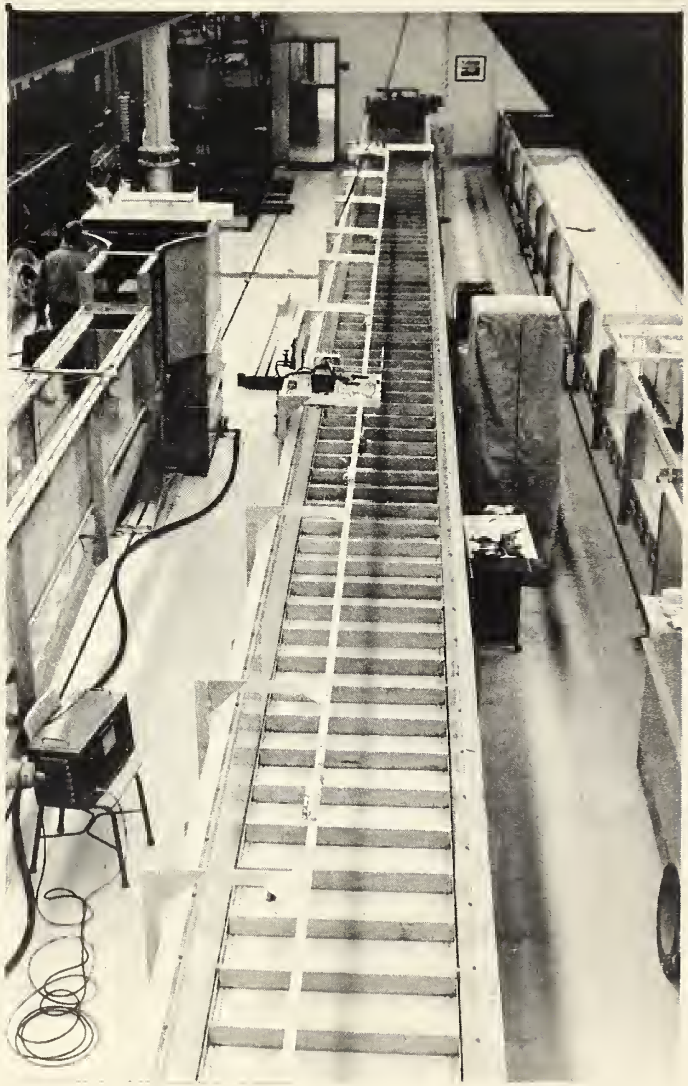
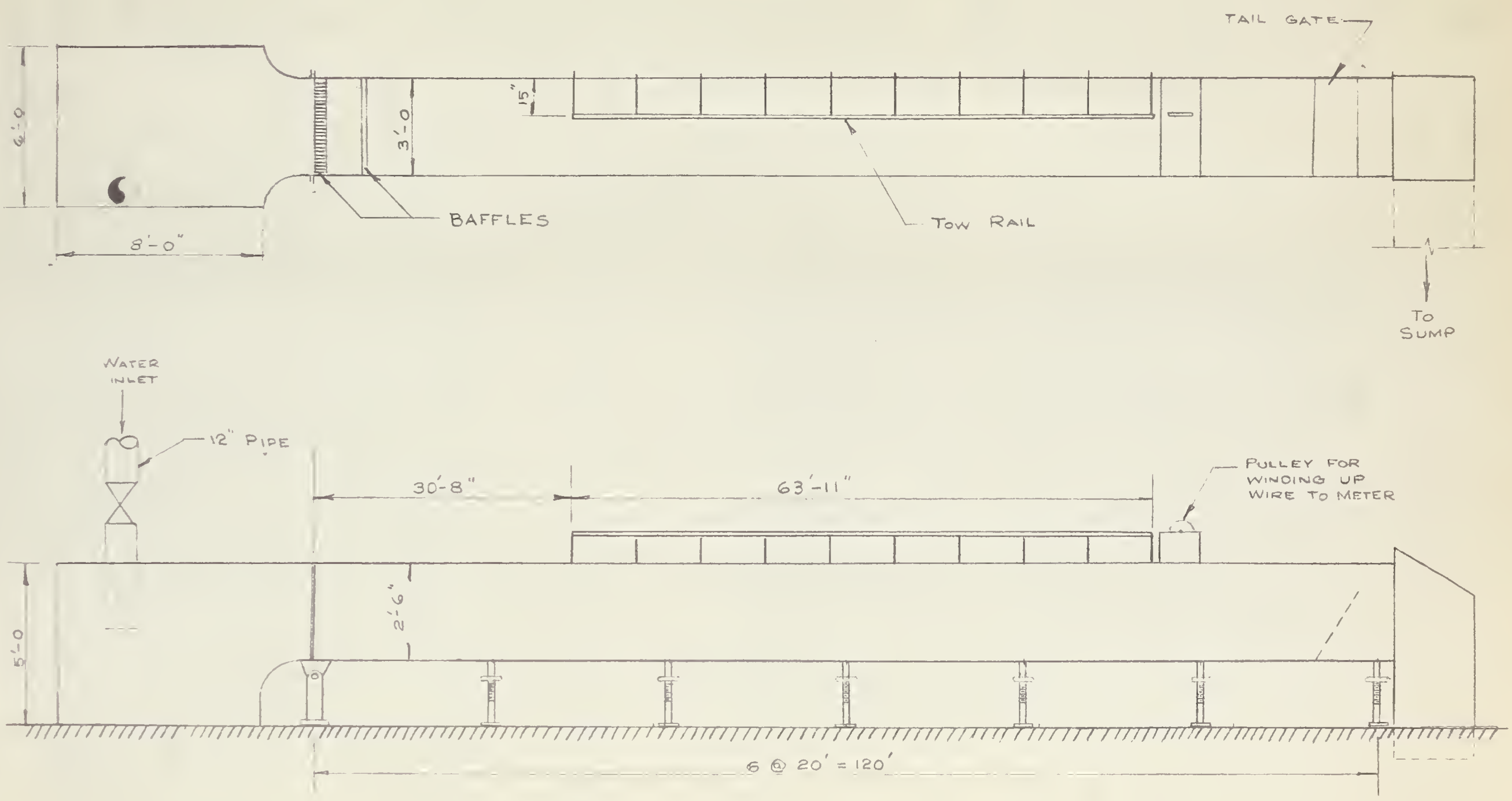


Plate 4 - Tow Rail and Motor



DETAILS OF FLUME
(NOT TO SCALE)

FIGURE 1

can be seen on Plate 5.

Attached to the rail at various intervals were six micro switches and tripping wheels. The two end switches shut the motor off as the dolly approached the ends, while the middle four were spaced throughout the test section. Plate 6 shows a typical micro switch and the trip mechanism while Figure 2 gives the locations and wiring details of the micro switches. The motor was wired so that once the end switches had been tripped it was necessary to reverse the motor before it could be started again.

The current meter is equipped with an electrical contact which conducts during half of each revolution, the output recorded is thus a square wave form as shown in Figure 3. The output from the meter was obtained from wires running to the dolly at one end and attached to a pulley at the downstream end of the tow rail. Pickups were arranged on one end of the axle passing through the pulley to carry the output to a strip chart (Sanborn) recorder. At the other end of the axle a cable and weight provided torque to the pulley to wind the wire as the dolly was towed along. A view of this can be seen on Plate 7.

Current was supplied to both the micro switches in the test section and the current meter from flashlight batteries. The signals from each were taken to the recorder and registered on two channel recording paper simultaneously. The resistances shown in series with the micro switches were installed to obtain a definite indication on the recorder as each was tripped while those in series with the batteries were installed only to extend the life of the batteries.

The recorder was a Sanborn D.C. Coupling Preamplifier,

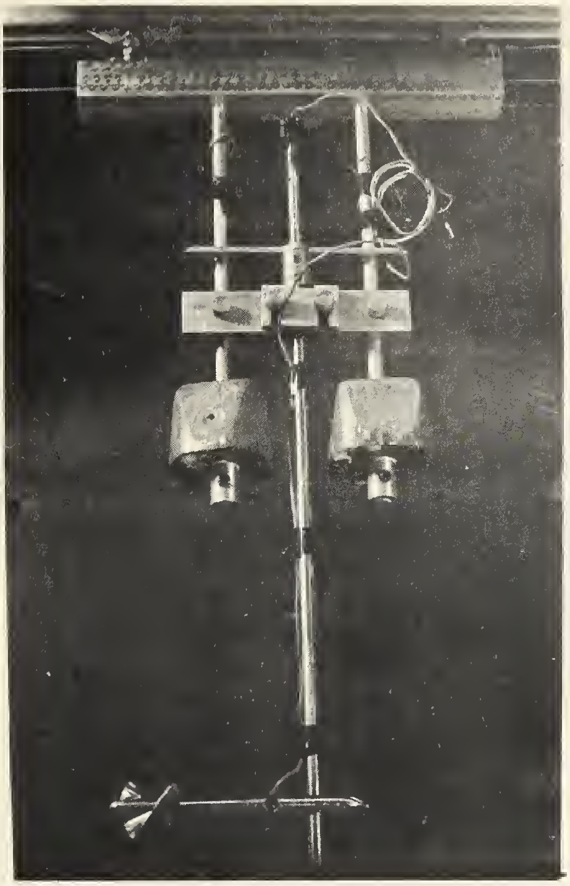


Plate 5 - Towing Carriage With Meter

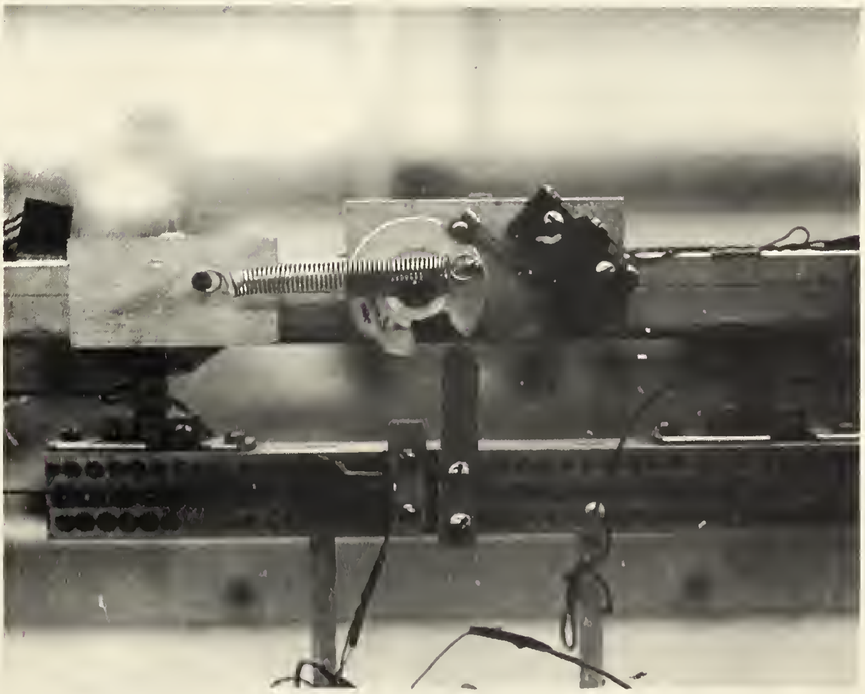
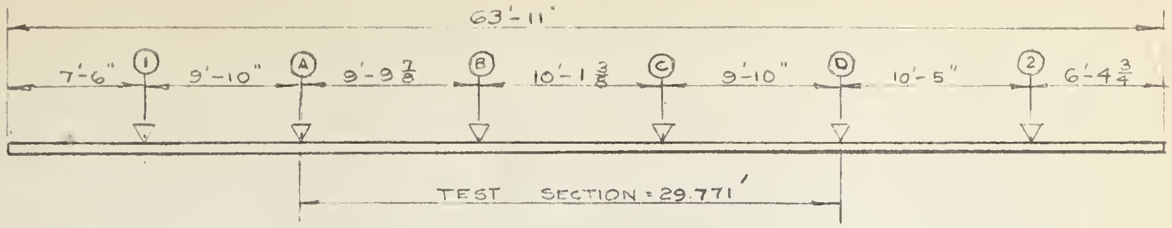
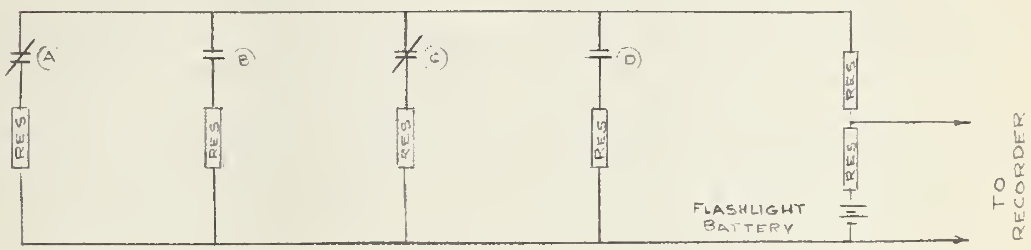


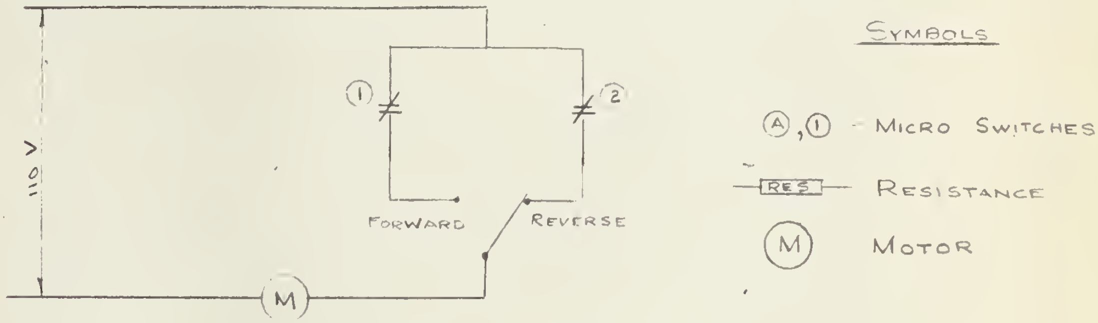
Plate 6 - Micro Switch and Trip Mechanism



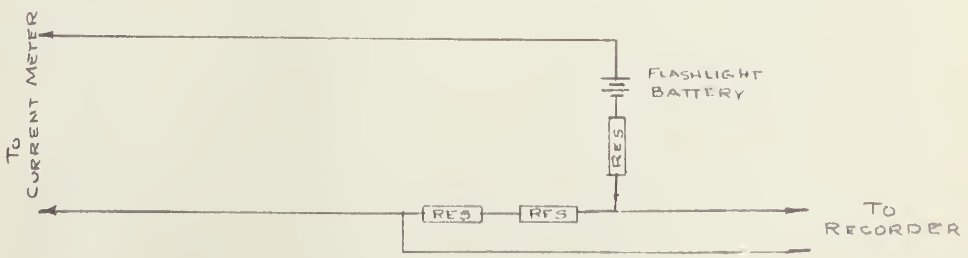
MICRO SWITCH LOCATIONS
(NOT TO SCALE).



WIRING DIAGRAM FOR TEST SECTION



WIRING DIAGRAM FOR MOTOR



WIRING DIAGRAM FOR CURRENT METER

MICRO SWITCH LOCATIONS
AND WIRING DIAGRAMS

FIGURE 2.

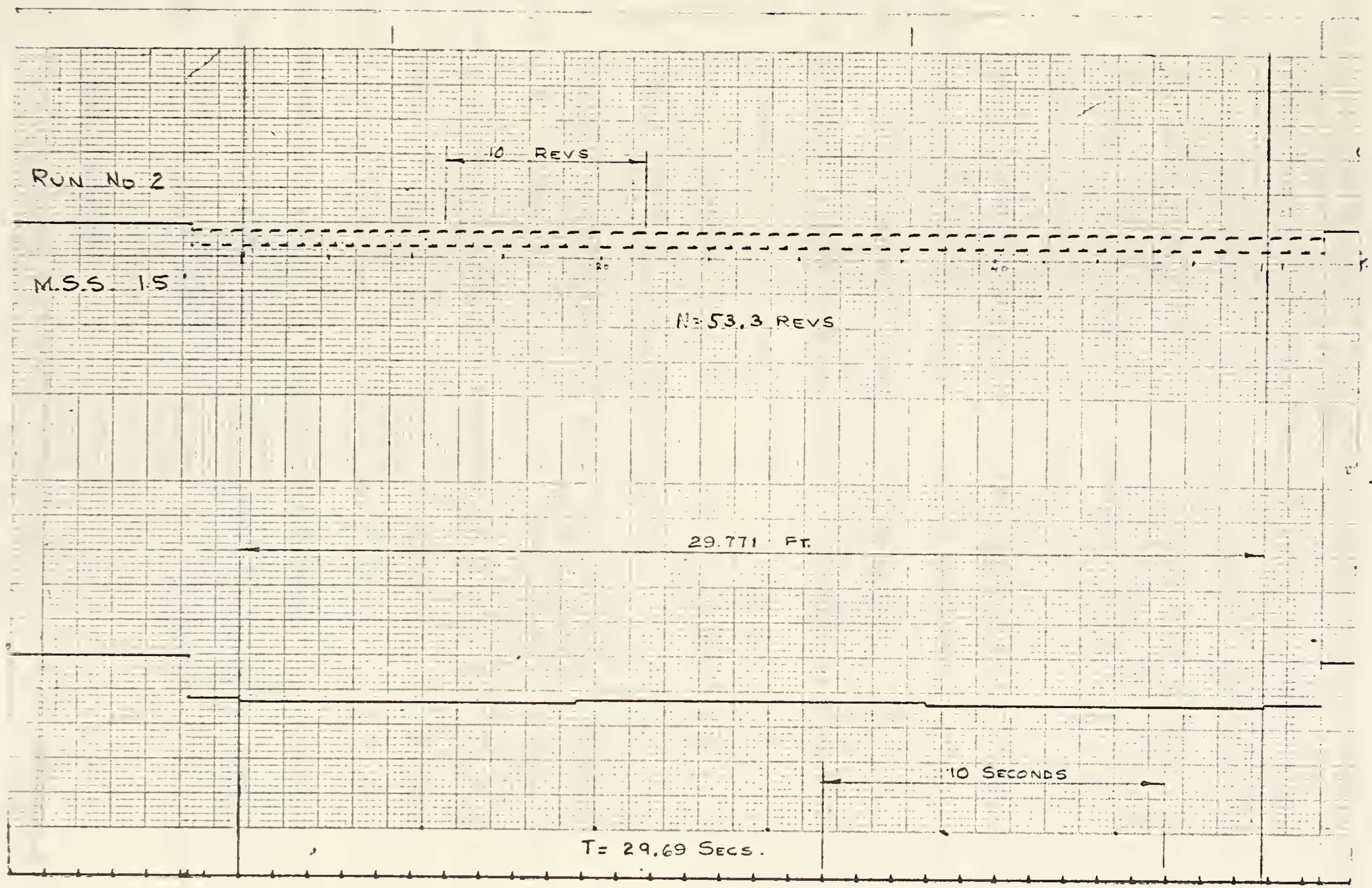


FIGURE 3. - TYPICAL CHART SECTION, FULL SIZE

Model 150 - 1300, equipped with two channel recording paper and is shown in Plate 8. Each second of time elapsed was recorded at the extreme edge of the paper while the runner revolutions and tripping of micro switches were recorded on the two channels as shown on Figure 3. Nine paper speeds could be used: 0.25, 0.5, 1.0, 2.5, 5.0, 10.0, 25, 50, and 100 mm/sec. depending on the velocity of tow and the velocity of the water; the usual being from 5 mm/sec. to 25 mm/sec.

The current meter used throughout this investigation was a Laboratory Current Meter, Serial Number 10672, manufactured by the A. Ott Company, Kempten, Bavaria. The meter was supported by a rod onto which the meter was clamped as shown in Plate 5. Three propellers were used: No. 1 with a pitch of 0.05 m (0.1640 ft.); No. 2 having a pitch of 0.1 m (0.3281 ft.); and No. 4 having a pitch of 0.5 m (1.6404 ft.).

The water was pumped from a sump tank through a 12-inch pipe into a tank at the head of the flume. The maximum discharge available was approximately 7 c.f.s. Velocity profiles were taken at three locations throughout the length of the test section to determine whether the profile was uniform. The velocity contours for the case of turbulent flow and a smooth bed can be seen in Figure 4. The velocities were determined by using the current meter and the still-water calibration curve.

4.2 TEST PROGRAM

The original plan for this study was to measure the degree of turbulence present in the flow using a hot film anemometer and then to calibrate the current meter in the same flow. Using this method it was hoped to obtain a relation between the

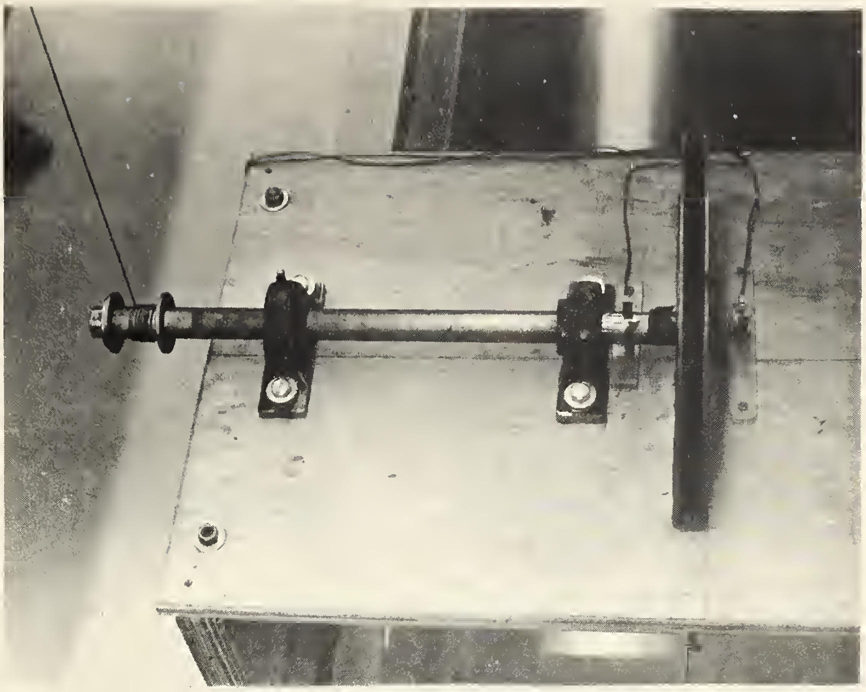
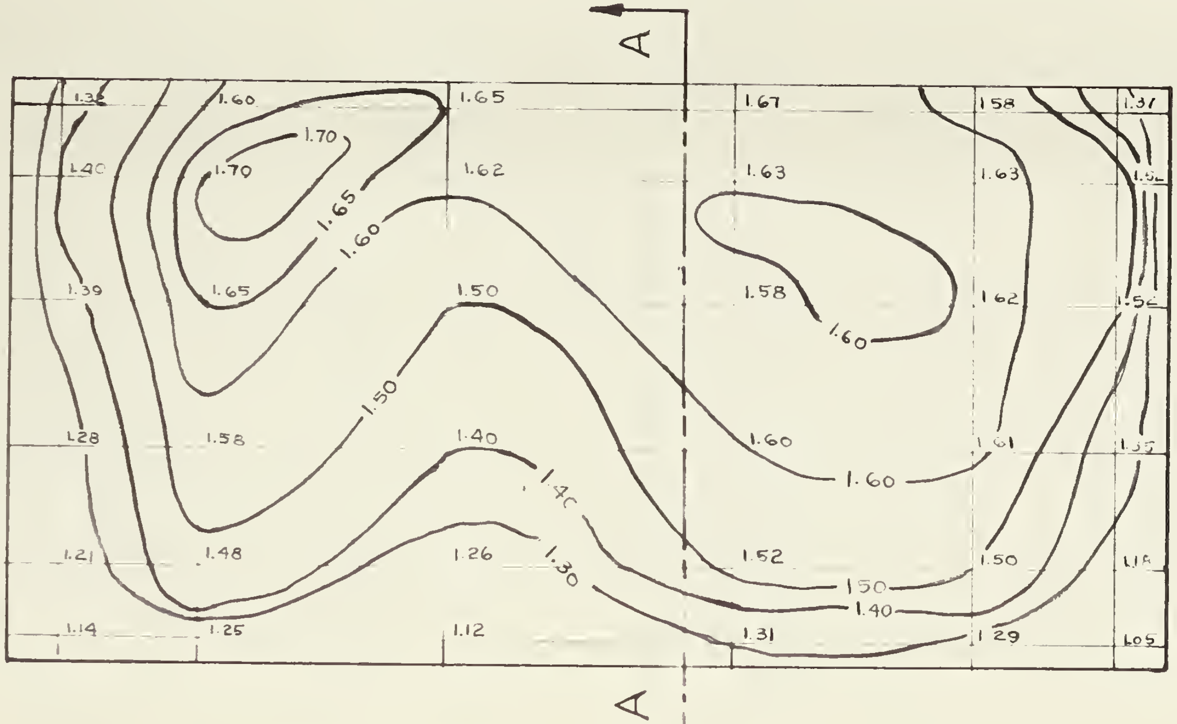
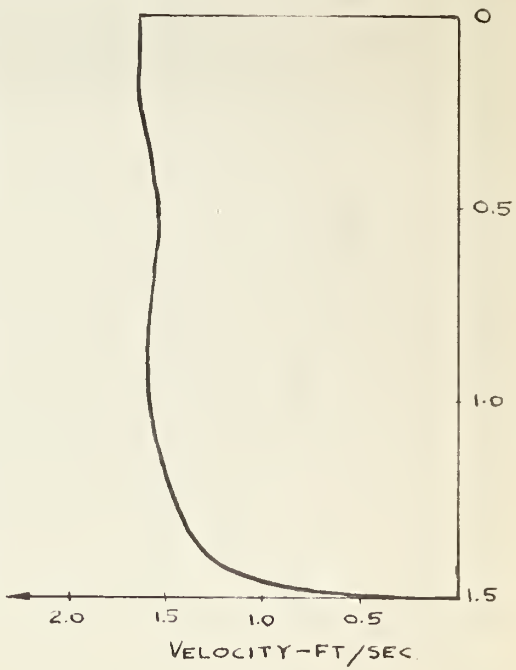


Plate 7 - Spooling Pulley and Pick - Up Arms To Record Pulses From Meter

Plate 8 - Sanborn Recorder



Distribution of Velocity Components
Facing Upstream
Turbulent Flow - Smooth Bed



Section A-A
Velocity Distribution
Along the "Line of Tow"

Figure 4

turbulent field and the error between still-water and turbulent water calibration curves. As a hot-film anemometer could not be obtained on time the photographic method was tried (see Appendix A) but no satisfactory results obtained. The remaining part of the investigation was then devoted to obtaining the calibration curves for the different fields of turbulence and seeing if the rating curves changed and if so, to what extent.

The first experiments were to rate the current meter by dragging it at constant velocities through still water at various distances from the bed and surface. A linear relation of speed of drag to the revolution of the meter propeller per second was expected, when remote from sides and surface. Near the bed, sides, and surface it was expected that this relation might change.

In the next series of tests, the meters were rated with the water flowing, keeping the same breadth to depth ratio (b/d). The meter was towed along the same lines of flow as before, but both upstream and downstream.

4.3 TESTING PROCEDURE

4.3.1 Data Recording

The test data were recorded on the recorder mentioned previously. This instrument uses a heat sensitive paper and recording pens whose temperature can be recorded electrically, enabling a clear trace of the oscillations in electric pulses from the current meter and micro switches over the test section to be recorded. Current meter revolutions, tripping of the micro switches, and the time in seconds were all recorded on the two channel recording paper; an example of which is shown

in Figure 3. From these recordings the tow velocity and meter revolutions per second could be calculated. The combined data and analysis sheets are shown in Appendix B.

The tests were numbered in the following manner: those beginning with the letter S refer to the still-water calibration tests; those with the letters TS refer to tests carried out in turbulent flows with the bed of the flume in its original state, (i.e.,smooth bed), hence, TS (Turbulent-Smooth); and those tests which were carried out in turbulent flows with a rough bed consisting of boards placed perpendicular to the flow on the flume bed were labelled with the letters TR (Turbulent-Rough). The boards were 1 inch thick, 3 inches wide, and 3 feet long, and were placed edgeways across the flume. Their spacing was one foot and ran for a distance of 100 feet from the head of the flume. Plates 3 and 4 show them in place.

Water depths were measured using a point gauge but due to the surface roughness in turbulent flows, they could only be read to plus or minus 0.01 feet. The depth was kept as close to 1.5 feet as possible but most care was taken to have uniform flow over the test section which entailed adjusting the valve opening and/or gate setting until the depth was constant throughout.

4.3.2 Description of Tests

Tests S1, S2, S3.

The flume was leveled and water completely at rest during each calibration run. A minimum time interval of ten minutes was allowed between successive calibration runs.

Current meter depths for each test were as follows:

S1, 1 inch below surface; S2, 9 inches; and S3, 17 inches. The meter was towed at five different calibration speeds ranging from 0.3 to 6.8 feet per second. A minimum of three runs were made at each speed. The water depth was 1.5 feet throughout all the tests. Propeller No. 2 was used in all tests.

Tests S4, S5, S6.

These tests were carried out in the same manner as those above but Propeller No. 4 was used throughout. Current meter depths were in the respective order 1" below surface, 9 inches, and 17 inches.

Tests S7, S8, S9.

These tests were carried out all at the same depth, being 9 inches below the surface. The water depth was 1.5 feet. These tests were performed nearly two months after the previous ones. During that time it was found that it would be better to obtain results over a large range of tow velocities, therefore only one run was recorded at each calibration speed.

For each of these tests the propeller used was different, being as follows:

Test S7 - propeller number 1.

Test S8 - propeller number 2.

Test S9 - propeller number 4.

S7, and S9 also served as a check on the calibration in tests S2 and S5, respectively; and to see if any change had taken place in the calibration curves over that period of time.

Tests TS 1, TS 2, TS 3.

In this series of tests No. 2 propeller was used through-

out and the flume was placed on a slope of 0.02 percent. After the valve opening and tailgate setting had been adjusted to give a uniform depth over the test section, the depth was found to be 1.52 feet. Lines of tow were at depths 1", 9", and 17", respectively.

The meter was towed in each test in the following manner:

A. Upstream, with the meter facing upstream.

B. Downstream, with the meter facing upstream but at a tow velocity slower than the flow velocity along the line of tow of the meter.

C. Downstream, with the meter facing downstream but at a tow velocity faster than the flow velocity along the line of tow of the meter.

The calibration speeds were varied throughout the range of the apparatus; a minimum of two runs taken at each calibration speed.

Tests TR 1, TR 2, TR 3.

The slope was changed to 0.24 percent and the rough bed of planks installed. The centre line of the planks was taken as the base for depth measurements thereby making it necessary to place the meter at a depth 14 7/8 inches below the surface for Test TR 3; this being 1 inch above the boards. Tests TR 1 and TR 2 remained similar to the others having the meter placed at a depth of 1" and 9" respectively. The same procedure of towing was used as in Tests TS 1, TS 2, and TS 3. Propeller Number 2 was used throughout these tests.

Tests TR 4, TR 5, TR 6.

The slope was kept at 0.24 percent and the rough bed left in place. The depth of flow was 1.46 feet. The meter was located nine inches below the surface for all these tests. Propellers number 1, 2, and 4 were used for tests TR 4, TR 5, and TR 6, respectively. Only one run was carried out at each calibration speed but the entire speed range of the apparatus was covered allowing approximately eighteen calibration speeds for each direction that the meter was facing.

4.3.3 General Testing Procedure

The first series of tests was carried out to rate the current meter in still water. The rating was performed with the meter in three locations: just submerged, at mid-depth, and just above the floor of the flume. This was to establish whether the proximity to a boundary changed the rating curve.

In turbulent flows a slightly different approach had to be used. As in most laboratory and field studies of this nature, there is no method available to determine the velocity along the "line of tow" of the meter. Pitot tubes have been used in a number of cases but they are known to be subject to errors in turbulent water. One was used in this investigation only as a check, since the pitot tubes available were not calibrated and the meniscus of the manometer fluctuated considerably. Discharge measurements as a check were not considered as a traverse of the flume was impossible since the tow rail was in a fixed position. It was therefore necessary to find the velocity along the "tow line" of the meter by using the meter itself and by towing it in the upstream and downstream directions.

The easiest way to describe this procedure is to consider an ideal case with a frictionless meter and laminar flow. If the meter was facing upstream, then it would be possible to vary the speed of tow downstream until it was such that the meter propeller did not revolve at all; in other words, the tow speed downstream exactly equalled the velocity of the water. Similarly when the meter is facing downstream, the tow speed could be varied until it was exactly the same as the water velocity along the "line of tow" of the meter; this tow velocity should be the same in both cases when a frictionless meter is considered. In actual practice where friction comes into effect, these two velocities will be different. In the former case the tow velocity will be less than the actual water velocity and in the latter case it will be more than the water velocity. In turbulent flows, as the tow velocity approaches the velocity of the water, the eddies and whirls present in the flow cause the propeller to rotate erratically, thereby making it necessary to find the water velocity by extrapolating the calibration curves for the meter facing in the upstream and downstream direction. Figures 10 and 11 show these lines which are discussed further in Section 4.4.

For the tests carried out in turbulent flows, the meter was placed facing upstream and towed upstream over the range of speeds of the apparatus, and downstream at various speeds, but not exceeding the water velocity or the velocity which could cause the propeller to rotate in the negative direction. The meter was then turned to face downstream and towed at speeds exceeding the water velocity along the "line of tow" of the meter.

In all tests the meter was aligned so that its axis was parallel to the sides of the flume. Since the meter itself was submerged, measurements were made to an arm attached to the rod support; the arm was set parallel to the meter axis by using a simple jig.

4.4 RESULTS AND ANALYSIS OF DATA

4.4.1 Still Water Calibrations

The results of the calibration in still water are shown in the data and analysis sheets in Appendix B, Tests S1 through S9. They are shown graphically for propellers 2 and 4 in Figures 6 and 7, respectively. The regression line was calculated for the data using the method of least squares; all calculations being done on an I.B.M. 1620 Computer. Table 1 gives the equations of the lines and the regression coefficients for each set of data.

The assumption that the calibration curve can be represented by a straight line is not quite true. As the value of N approaches zero, the shape of the curve becomes hyperbolic as shown in Figure 5. Reference 15 discusses these curves in detail. For the still water calibrations, the assumption of a straight line relationship will not produce excessive errors, the curves being used for comparative purposes only.

The above method of plotting is convenient for recording the results of meter-rating tests. It is not suited to determine the accuracy of the rating or to compare different ratings. This is because the physical inter-relation between the water velocity, the rotation of the meter propeller, and the mechanical and hydraulic resistances occurring in the meter are not made

TABLE 1

EQUATIONS OF REGRESSION LINES

STILL-WATER CALIBRATIONS

Test No.	Prop. No.	Meter Location	Equation of Regression Line	Coefficient of Regression	Remarks
S1	2	1"	$V_n = 0.3392\ N + 0.0516$	0.99999	
S2	2	9"	$V_n = 0.3384\ N + 0.0557$	0.99999	
S3	2	17"	$V_n = 0.3369\ N + 0.0596$	0.99999	
S4	4	1"	$V_n = 1.6650\ N + 0.0199$	0.99997	
S5	4	9"	$V_n = 1.6776\ N - 0.0208$	0.99991	
S6	4	17"	$V_n = 1.6499\ N + 0.0274$	0.99991	
S7	1	9"	$V_n = 0.1658\ N + 0.1541$	0.99994	
S8	2	9"	$V_n = 0.3369\ N + 0.0631$	1.00000	Verification of calibration curve.
S9	4	9"	$V_n = 1.6259 \quad + \quad 0.0918$	0.99989	Verification of calibration curve.

apparent. Both Ott (Ref. 20) and Troskolanski (Ref. 15) found it better, with the same abscissas, to plot as ordinates the corresponding velocity slip in percent of the tow velocity; that is, the difference $\Delta V = V - kN$, between the velocity of the towing carriage and the axial advance of the propeller calculated from k, the pitch of the propeller, and N, the number of revolutions per second.

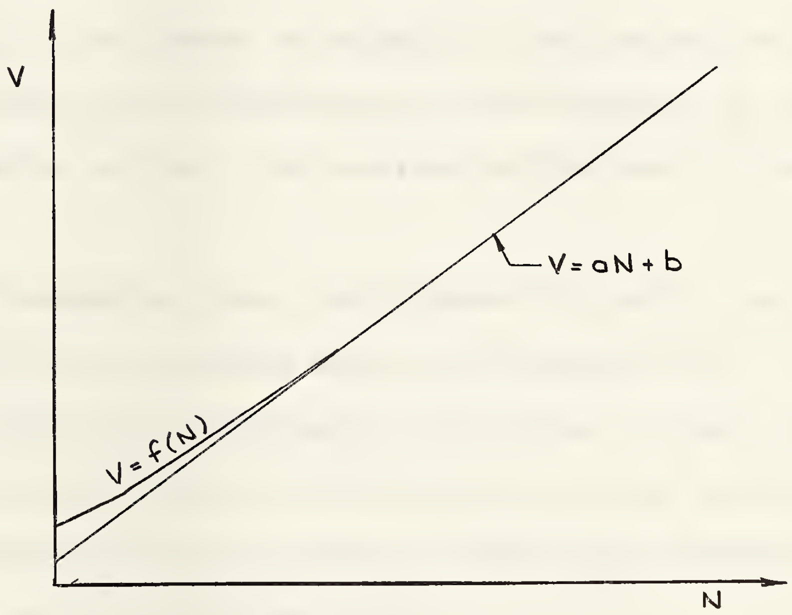


Figure 5

Example Curve $V = f(N)$

This can also be expressed as a percentage of the tow velocity. The properties of the instruments, the special influences of the boundaries, and the towing procedure are then more clearly defined than in the first method of plotting. Figures 8 and 9 show these plots for propellers 2 and 4, respectively, for the three depths. It should be pointed out that to obtain data for these plots no assumptions, such as the calibration curve being a straight line, had to be made, but data were taken directly

from the original recordings.

Figure 8 indicates that there is a reduction in the propeller slip as the bed of the flume is approached, this being in the order of one percent for values of N greater than 2, the lower limit for which this propeller should be used. This would result in a one-half percent error in velocity if the mid-depth curve was used throughout; the error being one of excess near the bed and deficiency near the surface.

The curves drawn on Figure 9 are similar to those of Figure 8, taking into consideration the changing of the abscissa and ordinate scales. The maximum difference in percent slip is 1.2%.

In comparing these two figures to each other, the large reduction in the percent slip for propeller No. 4 can be attributed to the reduced hydraulic resistance of the water flowing around the rotor, and to the decrease in the mechanical resistances caused by the reduction in the thrust placed on its bearings due to its increased pitch.

Tests S7, S8, and S9 were carried out at the completion of all the testing. Tests S8 and S9, respectively, were carried out to verify the original calibration of propellers 2 and 4, while Test S7 was to calibrate propeller No. 1.

4.4.2 Calibration Curves Determined in Turbulent Flows

As previously mentioned, in the tests carried out in turbulent flows, the velocity of the water along the "line of tow" of the meter had to be determined before a calibration curve could be calculated. Unlike the still-water tests, the revolutions recorded by the meter did not represent the tow

velocity, although there was a direct relationship. Figures 10 and 11 illustrate the manner in which the flow velocity was obtained, the former being for the smooth bed and the latter for the rough bed. Both tests were carried out with the No. 2 propeller.

A line was fitted to the data using the method of least squares by considering each direction in which the meter was facing separately. Tables 2 and 3 give the regression lines and coefficients for the "TS" and "TR" tests, respectively. Assuming a linear relationship, the intercept for the meter facing in the upstream and downstream directions was calculated at each location. The absolute value of the average intercept for each test could then be added to the tow velocity and the velocity, (V_n), relative to the meter, obtained from:

$$V_n = \left| V_T + \text{Intercept} \right|$$

The absolute value had to be used since the tow velocity was taken as being positive in the upstream direction. When the meter was being towed downstream faster than the flow velocity, the tow velocity was negative. The velocity of the water relative to the meter was positive.

The V_n and corresponding N values were plotted to obtain the required calibration curve. Figure 12 compares the resultant curves for the two turbulent fields with the still-water calibration. The equations are given in Table 4 for all the cases. Tests TR 4, TR 5, and TR 6 were carried out in water having the same turbulent field, the same water depth, but a different propeller used in each tests.

TABLE 2

EQUATIONS OF REGRESSION LINES

FOR V_T vs N

TURBULENT FLOW - SMOOTH BED

Test No.	Meter Facing	Meter Depth	Propeller No.	Equation of Regression Line	Coefficient of Regression
TS 1	Upstream	1"	2	$V_T = 0.3415\ N - 1.6080$	0.99989
	Downstream	1"	2	$V_T = -0.3368\ N - 1.7568$	0.99988
TS 2	Upstream	9"	2	$V_T = 0.3388\ N - 1.4736$	0.99995
	Downstream	9"	2	$V_T = -0.3403\ N - 1.5310$	0.99987
TS 3	Upstream	17"	2	$V_T = 0.3379\ N - 1.2551$	0.99969
	Downstream	17"	2	$V_T = -0.3357\ N - 1.3326$	0.99983

TABLE 3

EQUATIONS OF REGRESSION LINES

FOR V_T vs N

TURBULENT FLOW - ROUGH BED

Test No.	Meter Facing	Meter Depth	Propeller No.	Equation of Regression Line	Coefficient of Regression
TR 1	Upstream	1"	2	$V_T = 0.3408\ N - 2.1727$	0.99844
	Downstream	1"	2	$V_T = -0.3367\ N - 2.2024$	0.99376
TR 2	Upstream	9"	2	$V_T = 0.3339\ N - 1.5650$	0.99784
	Downstream	9"	2	$V_T = -0.3429\ N - 1.5570$	0.99525
TR 3	Upstream	14 7/8"	2	$V_T = 0.3381\ N - 0.8650$	0.99728
	Downstream	14 7/8"	2	$V_T = -0.3272\ N - 0.9612$	0.99783
TR 4	Upstream	9"	1	$V_T = 0.1703\ N - 1.5665$	0.99331
	Downstream	9"	1	$V_T = -0.1792\ N - 1.4168$	0.99216
TR 5	Upstream	9"	2	$V_T = 0.3206\ N - 1.3750$	0.98489
	Downstream	9"	2	$V_T = -0.3447\ N - 1.4526$	0.99535
TR 6	Upstream	9"	4	$V_T = 1.6858\ N - 1.5762$	0.99838
	Downstream	9"	4	$V_T = 1.6559\ N - 1.6243$	0.99459

TABLE 4

EQUATIONS OF REGRESSION LINES

FOR TURBULENT FLOW CALIBRATION CURVES

Test No.	Meter Depth	Propeller No.	Equation of Regression Line	Coefficient of Regression
TS 1	1"	2	V = 0.3398 N + 0.0745	0.99989
TS 2	9"	2	V = 0.3398 N + 0.0272	0.99995
TS 3	17"	2	V = 0.3372 N + 0.0390	0.99985
TR 1	1"	2	V = 0.3398 N + 0.0126	0.99851
TR 2	9"	2	V = 0.3368 N + 0.0037	0.99825
TR 3	14 7/8"	2	V = 0.3340 N + 0.0448	0.99834
TR 4	9"	1	V = 0.1696 N + 0.0029	0.99716
TR 5	9"	2	V = 0.3359 N + 0.0020	0.99390
TR 6	9"	4	V = 1.6789 N + 0.0189	0.99848

4.4.3 Comparison of Calibration Curves

The above method of plotting is unsatisfactory when comparing rating curves, as was found in the still-water cases. The results were plotted as the percent slip versus the propeller revolutions per second, comparing each set of data for the still-water and two turbulent fields (Figures 13, 14, and 15). Figure 13 shows the cases for the meter located 1" below the surface, the smooth turbulent cases plotting above the still-water curve S1, by as much as 1 1/4%. This amount is in addition to the 1/2% that curve S1 is above the mid-depth calibration curve from Test S2 (Figure 8). The results of the tests in turbulent flow with the rough bed (TR 2), shown on the graph by the crosses, follow no definite pattern; being distributed on both sides of curve S1.

With the meter located at mid-depth (Figure 14), the "TS" results plot fairly close to the still-water curve. The scatter of the points for the lower values of N are understandable since these were obtained with the meter being towed at a velocity downstream that was very close to that of the water; the meter, therefore, reacting to the eddies and whirls present to a greater extent than to the mean velocity, $\bar{U}$. For the "TS" data, all the points plot below the still-water curve resulting in an error of excess if the still-water calibration curve is used to determine velocities in turbulent waters. This is also seen in Figure 12, where the still-water calibration curve lies pretty well on top of curve TS 2.

Figure 15 shows the "TS" results to lie very close to the S3 curve; a curve through the points would not lie more than 1/2% below it. The "TR" data lies predominantly below the S3

curve indicating that it also shifts downwards, as was found in Figure 14. The magnitude of this shift is impossible to determine due to the scatter of the results.

Tests TR 4, TR 5, and TR 6 are represented on Figures 16, 17, and 18, respectively. All these tests were carried out in water having the same turbulence, and the same meter location, the only variable being the propeller used. While Figures 16 and 17 show the slip to decrease with the turbulent field using propellers 1 and 2, Figure 18 shows there is very little difference in percent slip with the different fields of turbulence for propeller No. 4, being close to the still-water curve. The results of Test TR 5 are doubtful due to the large number of negative slip values. This would result from the average intercept being low.

4.4.4 Discussion

Before any conclusions can be drawn from the results, the basic assumptions and errors must be discussed. For the still-water calibrations, the only assumptions made are that the calibration curve can be represented by a straight line. Since the curves were used for comparative purposes only, the errors due to this assumption will be tolerable. The errors in the curve obtained by plotting the percent slip versus the meter revolutions are those of the original data.

For turbulent flows, the assumption of the linear relationship between speed of tow and the revolutions of the propeller is an important one, for it is upon this assumption that the accuracy of both the final calibration curves and the percent slip curves depend. If each set of curves, (Figs. 10, 11), is

a mirror image of each other, the assumption that the average intercept value gives the flow velocity along the "line of tow" of the meter would be justified. This was not the case as seen by the 2 1/2% difference in slope in Test TR 2. The presence of any secondary flow or spiral motion of the water predominantly in one direction would cause the slopes and intercepts to vary.

As previously mentioned a pitot static tube was used only as a check since the one used was not calibrated, a coefficient of 1.0 being assumed, and the meniscus of the manometer fluctuated considerably although the slope of the manometer was one upon ten. The manometer readings were taken over at least a minute and these averaged. The results for the two fields of turbulence are given in Table 5 along with the average intercept value used for determining the curves.

TABLE 5

COMPARISON OF AVERAGE INTERCEPTS AND PITOT STATIC TUBE READINGS

	Velocity in Feet per Second	
Test No.	Average Intercept Value	Pitot Static Tube Reading
TS 1	1.6824	1.623
TS 2	1.5023	1.503
TS 3	1.2938	1.305
TR 1	2.1875	2.127
TR 2	1.5610	1.660
TR 3	0.9131	-

It must be remembered that the average intercept values represent the flow velocity over the entire length of the test secton, while the pitot tube only gives the velocity at the point at which it was located, in this case being at the centre of the test section.

The errors in recording the original data were mainly due to the mechanical construction of the trip mechanism. At low speeds the micro switches would sometimes trip sooner than at the higher towing speeds, resulting in the test section being a different length. This difference would never exceed 1/4" at each end, giving a maximum error of 0.15% in the velocity; the time as given by the recorder was taken as being true. The tow speed was considered constant over the test section.

The recording of the propeller revolutions created no problems since the speed of the recording paper could be varied to give reliable results to a tenth of a revolution in the majority of cases.

The changes in the meter rating curves due to damage or wear during the investigation was checked by recalibration of the meter. Figures 19 and 20 show the verifications for propellers 2 and 4, the difference being in the order of 1/4% in both cases. This was likely due to the noticeable wear in the bearings. Propeller No. 1 was only calibrated at the completion of the testing since it was only used once (Test TR 7), and this being only two days prior to its calibration.

As in other experiments of this nature, the lack of a reliable means of determining the actual flow velocity makes it necessary to draw the conclusions assuming the flow velocity to be true, but with the intention that these results become part

of an ensemble which could prove the conclusions made herein to be false.

It is unfortunate that there is no easy and reliable method to determine the turbulence present in the flow, and that the method tried in this investigation gave no useful results.

Quantitatively the results of this investigation are of little value. Qualitatively, they are of some use. The fact that the still-water calibration curves change as the surface and bed are approached has been known since current meters were first used. This resulted in the meters being calibrated in tanks which were supposedly large enough to enable the meter to be placed to be free from these effects. Fortunately, these errors, in some cases, are in opposite directions (Figures 8, 9), from the mid-depth calibration curves.

The results show that an increase in the degree of turbulence causes the meter to run faster. This can be seen by comparing the two turbulent fields in Figures 13, 14, and 15, or the decrease in slip as the bed is approached for the two cases, (if the percent slip decreases, then N must increase).

The author believes that the increase shown in the percent slip for the TS results in Figure 14 is due to an error in determining the flow velocity. A one percent error in this value is easily pictured. The change in the slip due to turbulence would then lie in the same direction from the still-water curve. It is reasonable that the effect of turbulence will follow some law resulting in the meter running faster as the turbulence increases, as the rest of the results indicate.

Figures 16 and 18 show that the propeller with the least pitch overestimates the most, that is, the more the error will

be if the still-water curves are used. This result is similar to that found by Chaix, (Ref. 9). The magnitude of the error is impossible to determine from the data. The results of Test TR 8 (Figure 17) were not considered due to the large discrepancy between its average intercept value and that of Test TR 4, both being carried out on the same day. The large number of negative values for ΔV in the data and analysis sheets are also evidence of an error.

The Reynolds' numbers in terms of the propeller diameter for the two turbulent cases had upper limits of approximately 21,000. The friction factors for the rough and smooth turbulent cases, respectively, were about 0.19 and 0.016. The above Reynolds' numbers and friction factors were calculated using the average velocity, based on a flow of 7 c.f.s. at a depth of 1.5 feet.

CHAPTER V - CONCLUSIONS

On the basis of tests performed on a rod-supported, screw type, laboratory current meter using blades of three different pitches, the following conclusions are drawn:

1. The use of still-water calibration curves determined at the mid-depth result in errors in the order of 1/2 percent when used for obtaining velocities within half a propeller diameter of the surface or bed.

2. When still-water curves are used for obtaining velocities in turbulent flows, they give results which are higher than actually exist, the turbulence causing the meter to speed up by roughly 2%.

3. In metering turbulent flows using the still-water calibration curve the error increases as the propeller pitch decreases.

The disagreement of Conclusion 2 with that found in previous research (see Section 3.2) cannot be explained. The lack of a reliable instrument to determine the actual flow velocity would account for part of this difference.

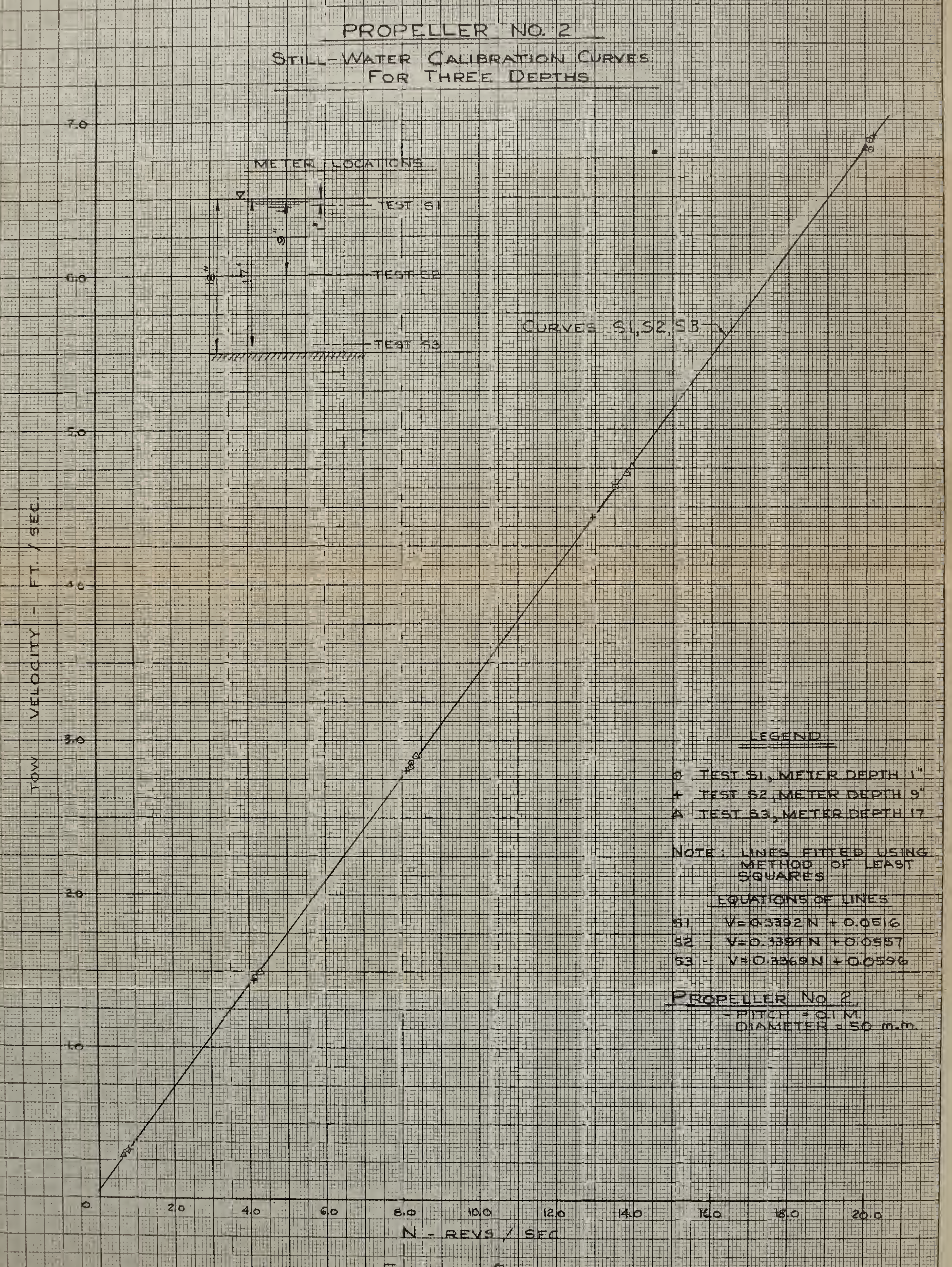

PROPELLER NO. 2
STILL-WATER CALIBRATION CURVES
FOR THREE DEPTHS
METER LOCATIONS
TEST S1
TEST S2
TEST S3
9"
17"
18"
CURVES S1, S2, S3
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
TOW VELOCITY - FT. / SEC.
N - REVS / SEC
LEGEND
⊙ TEST S1, METER DEPTH 1"
+ TEST S2, METER DEPTH 9"
△ TEST S3, METER DEPTH 17"
NOTE: LINES FITTED USING METHOD OF LEAST SQUARES
EQUATIONS OF LINES
S1 - V=0.3392 N + 0.0516
S2 - V=0.3384 N + 0.0557
S3 - V=0.3369 N + 0.0596
PROPELLER NO 2
- PITCH = 0.1 M.
DIAMETER = 50 m.m.

FIGURE 6

PROPELLER NO 4
STILL-WATER CALIBRATION CURVES
FOR THREE DEPTHS

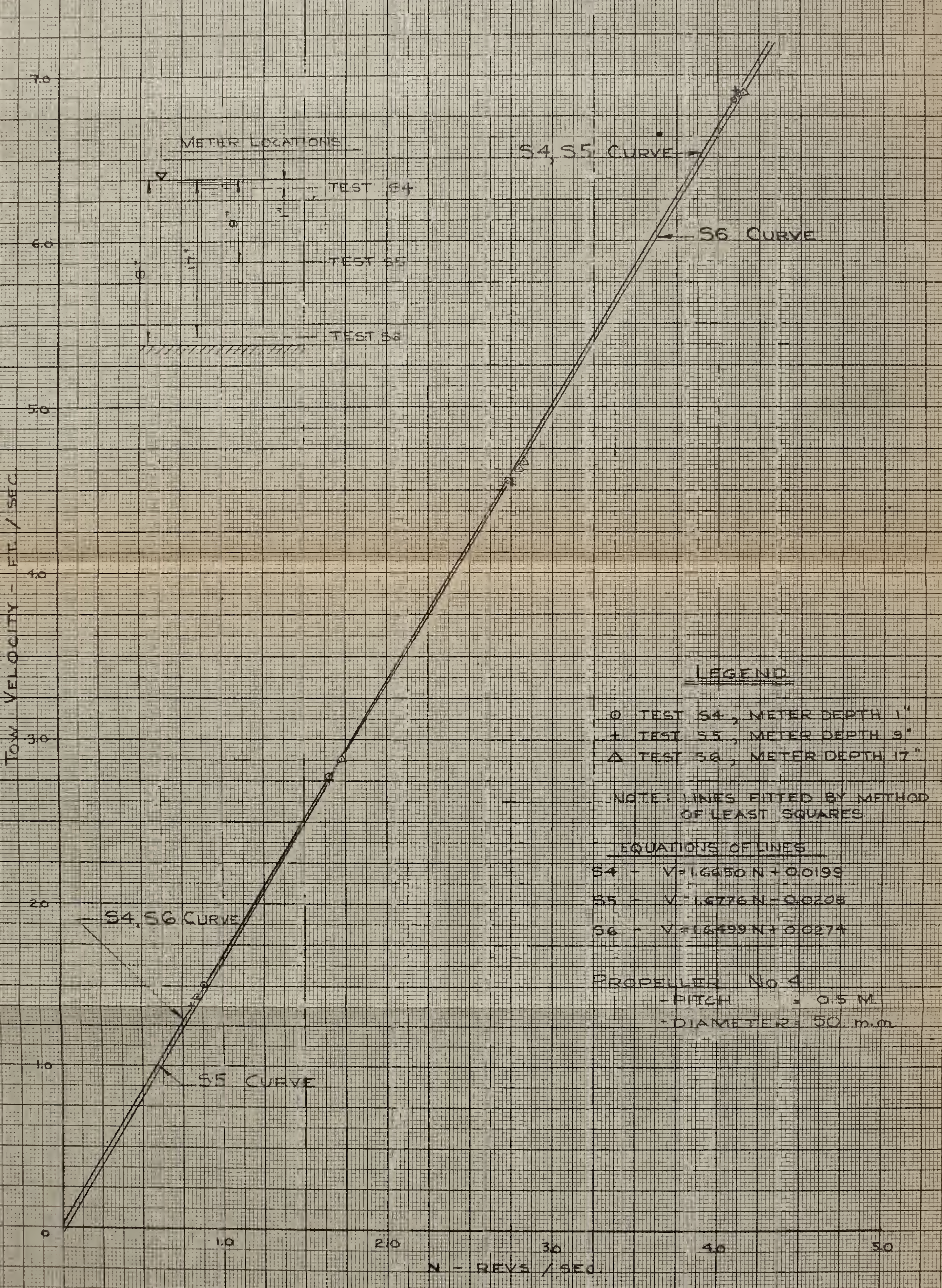


FIGURE 7.

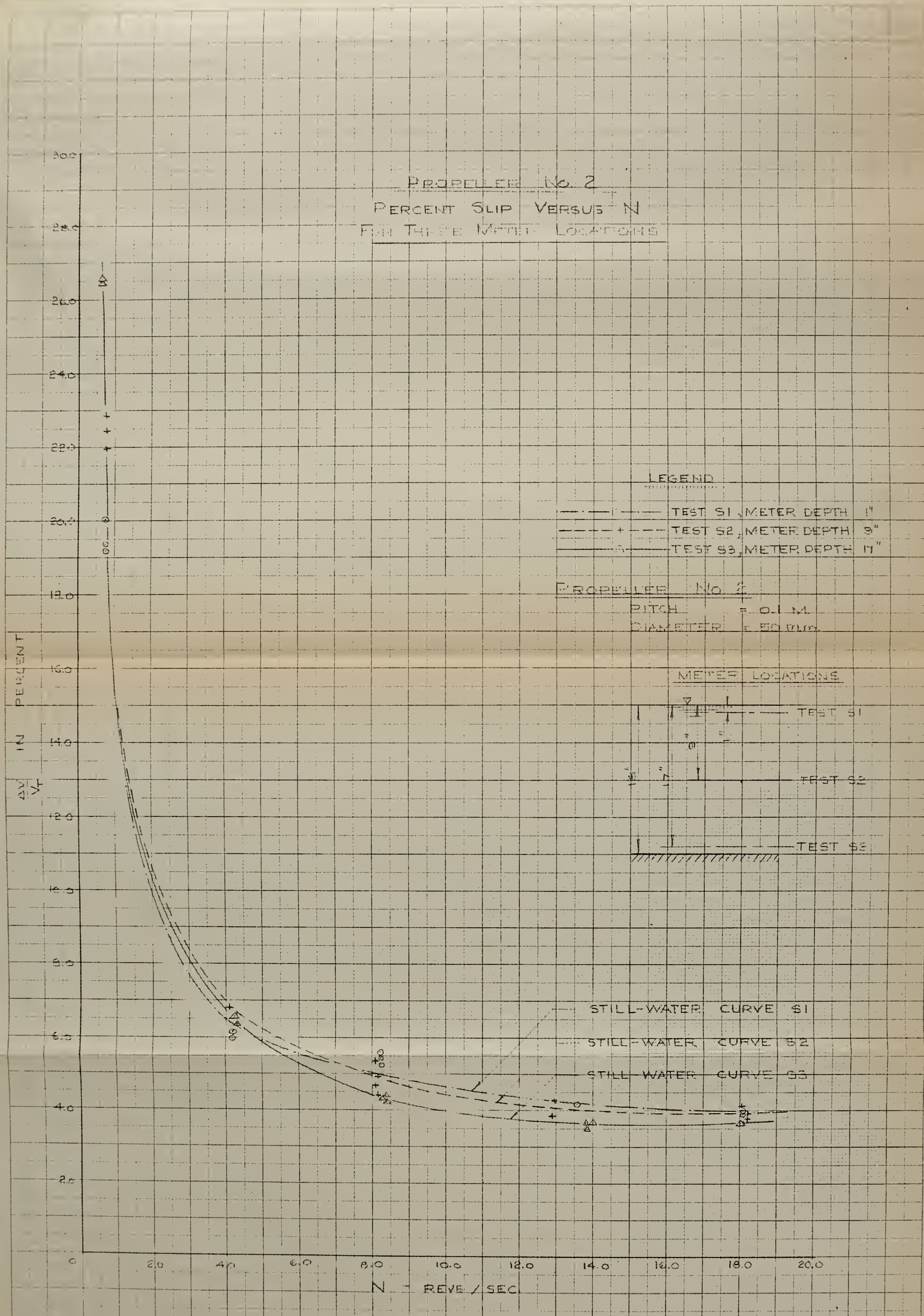
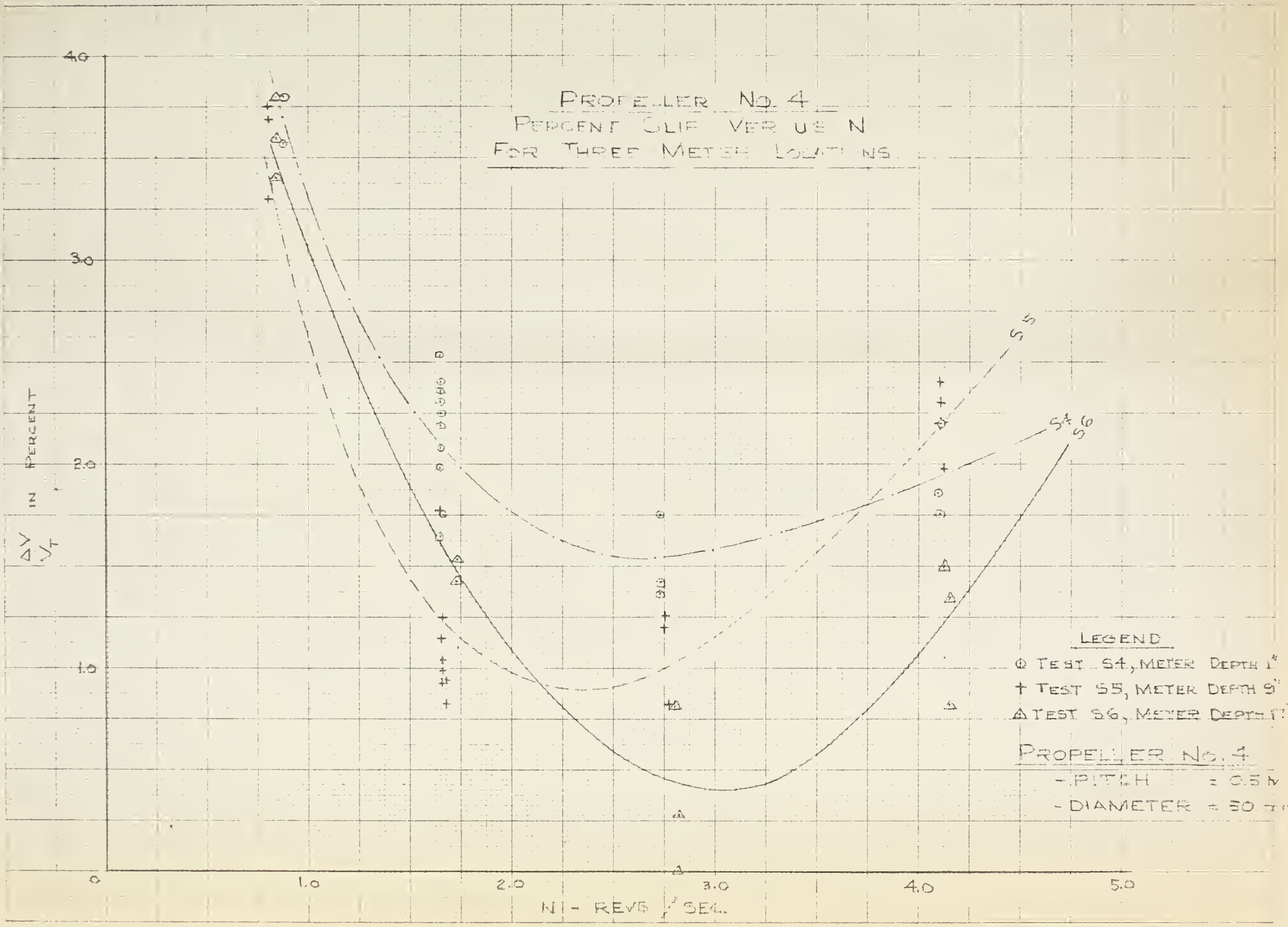

PROPELLER No. 2
PERCENT SLIP VERSUS N
FOR THREE METER LOCATIONS
LEGEND
TEST S1, METER DEPTH 1"
TEST S2, METER DEPTH 9"
TEST S3, METER DEPTH 17"
PROPELLER No. 2
PITCH = 0.1 M.
DIAMETER = 50 MM.
METER LOCATIONS
TEST S1
TEST S2
TEST S3
STILL-WATER CURVE S1
STILL-WATER CURVE S2
STILL-WATER CURVE S3
ΔV/V IN PERCENT
N - REVS / SEC
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0

FIGURE 8



PROPELLER No. 4
PERCENT SLIP VERSUS N
FOR THREE METER LOCATIONS
ΔV/V_T IN PERCENT
N - REVS/SEC.
LEGEND
⊖ TEST 54, METER DEPTH 1"
+ TEST 55, METER DEPTH 9"
△ TEST 56, METER DEPTH 17"
PROPELLER No. 4
- DIAMETER = 30

RELATION BETWEEN TOW SPEED, TOW DIRECTION AND PROPELLER REVOLUTIONS

TURBULENT FLOW - SMOOTH BED
PROPELLER No. 2

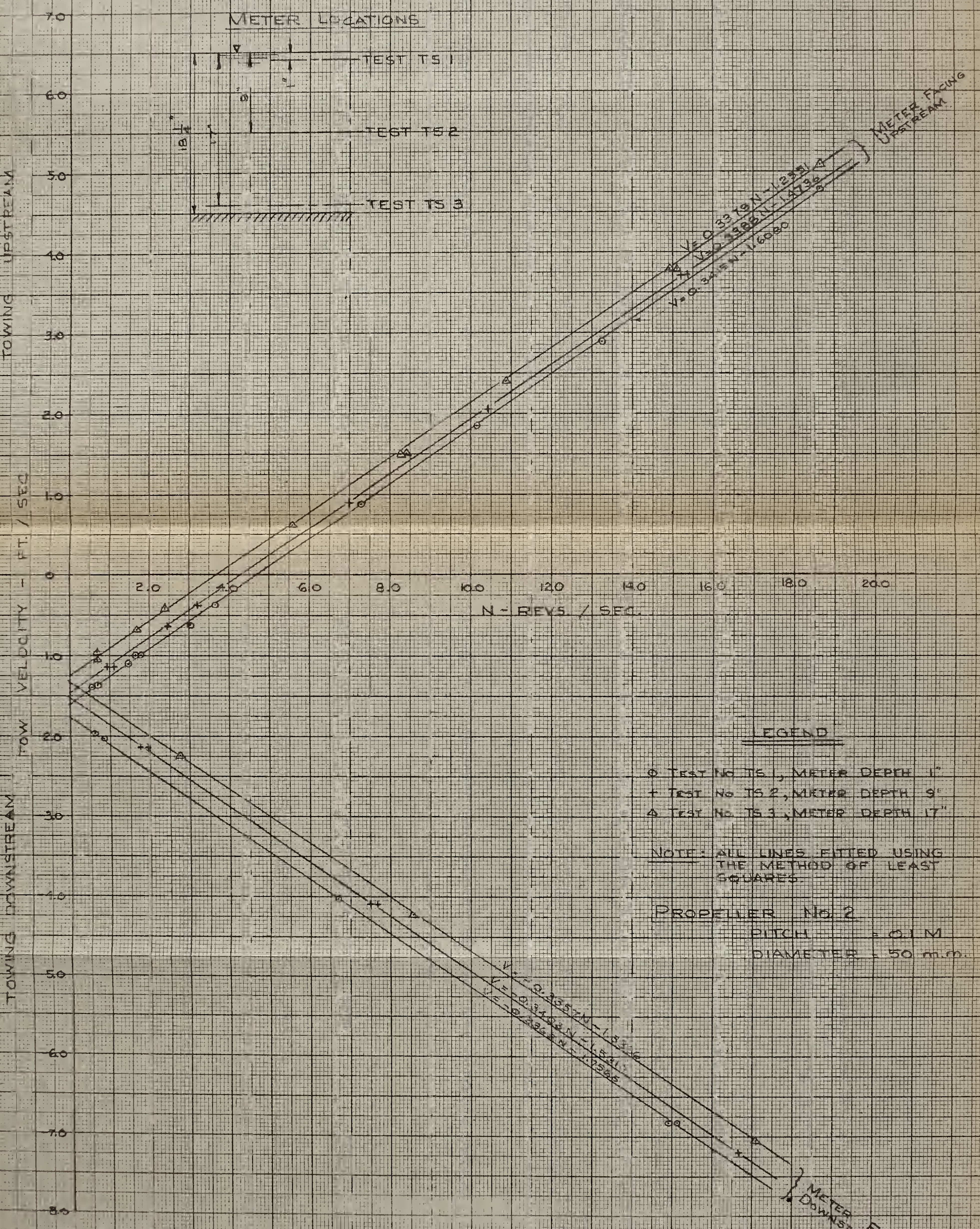


FIGURE 10

RELATION BETWEEN TOW SPEED, TOW DIRECTION AND PROPELLER REVOLUTIONS

TURBULENT FLOW - ROUGH BED
PROPELLER No. 2.

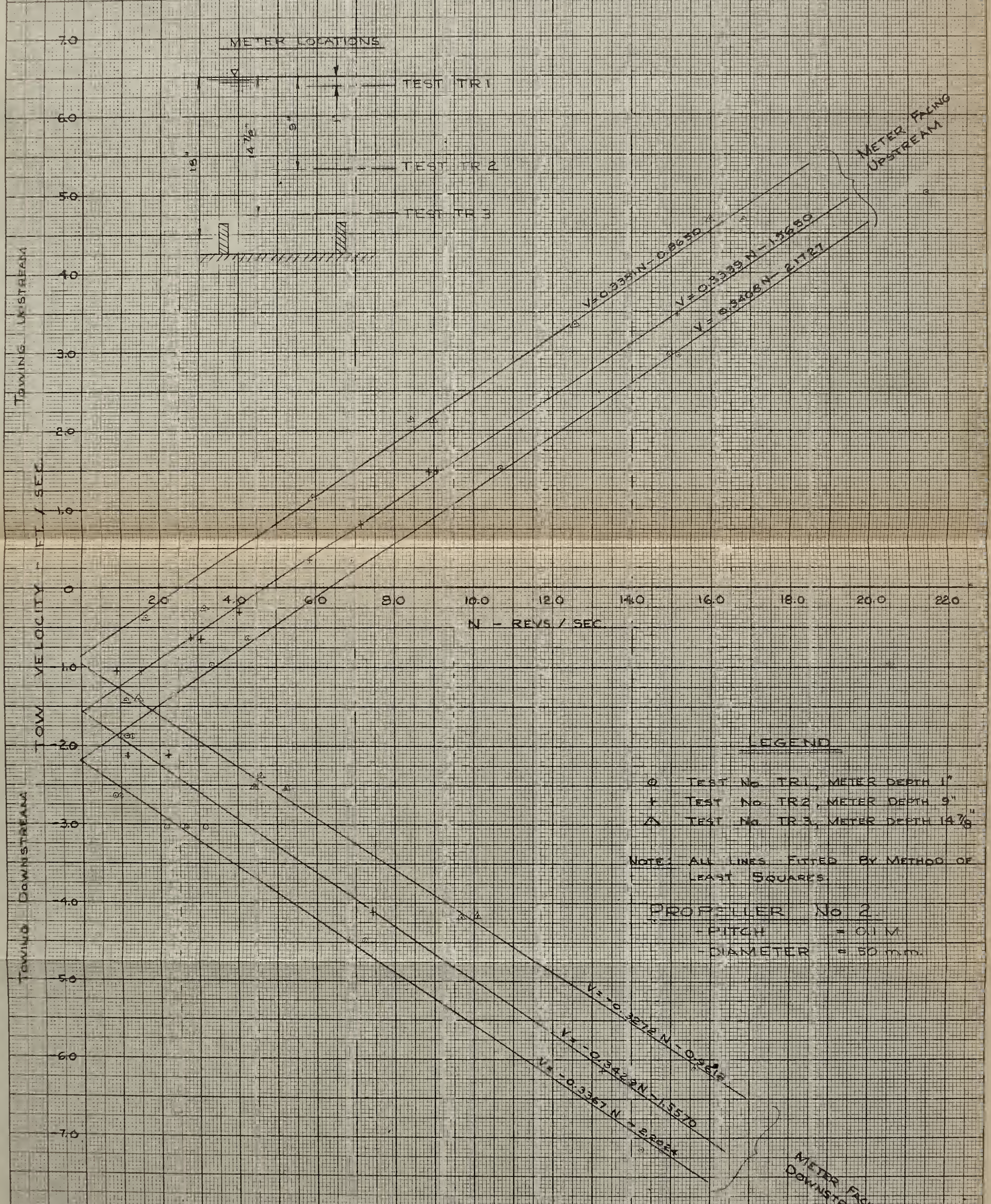


FIGURE 11.

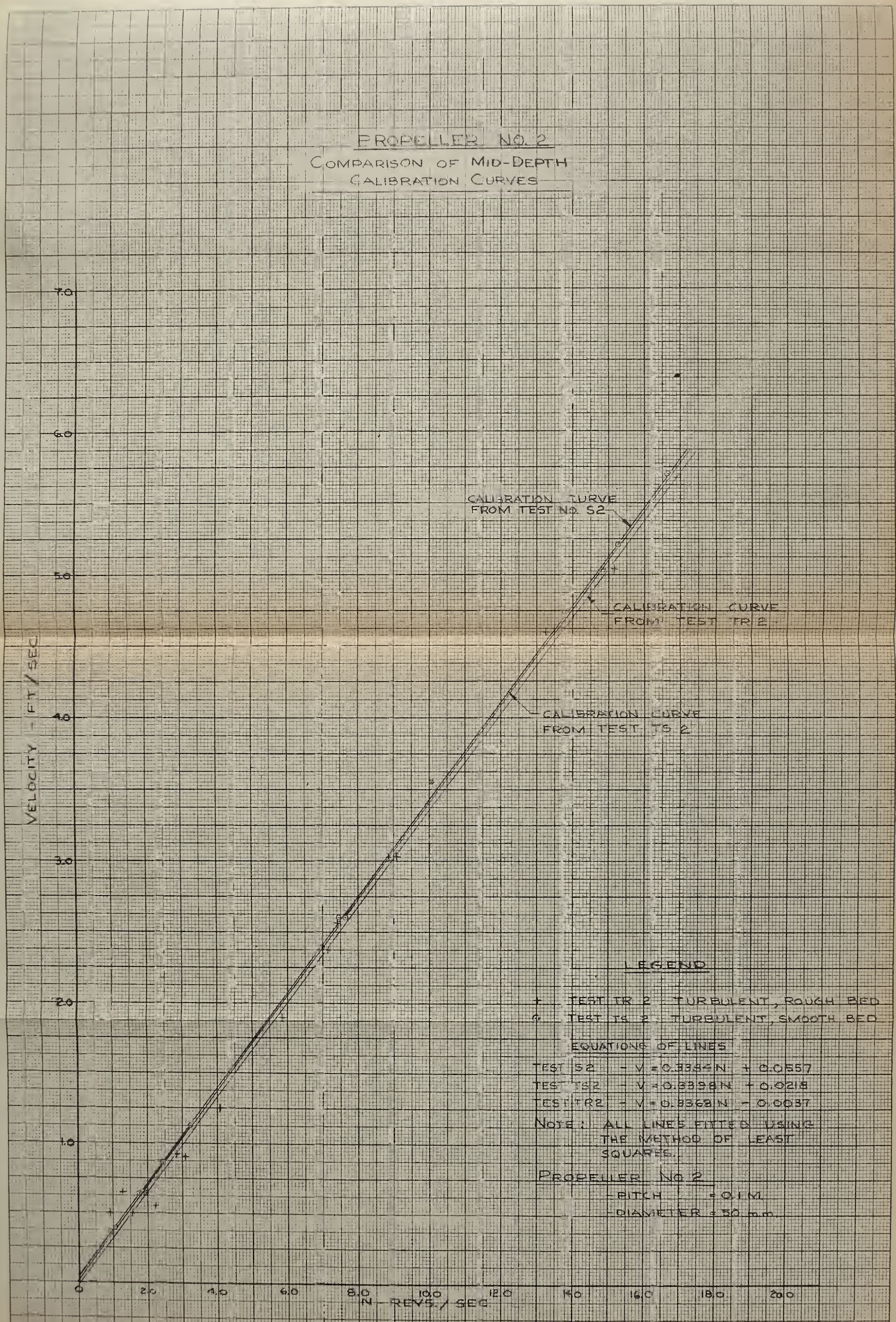

PROPELLER NO. 2
COMPARISON OF MID-DEPTH CALIBRATION CURVES
CALIBRATION CURVE FROM TEST NO. S2
CALIBRATION CURVE FROM TEST TR 2
CALIBRATION CURVE FROM TEST TS 2
VELOCITY - FT / SEC
N - REVS./ SEC.
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
1.0
3.0
5.0
7.0
LEGEND
+ TEST TR 2 - TURBULENT, ROUGH BED
o TEST TS 2 - TURBULENT, SMOOTH BED
EQUATIONS OF LINES
TEST S2 - V = 0.3384 N + 0.0557
TEST TS2 - V = 0.3398 N + 0.0218
TEST TR2 - V = 0.3368 N - 0.0037
NOTE: ALL LINES FITTED USING THE METHOD OF LEAST SQUARES.
PROPELLER NO 2
PITCH = 0.1 M.
DIAMETER = 50 mm.

FIGURE 12

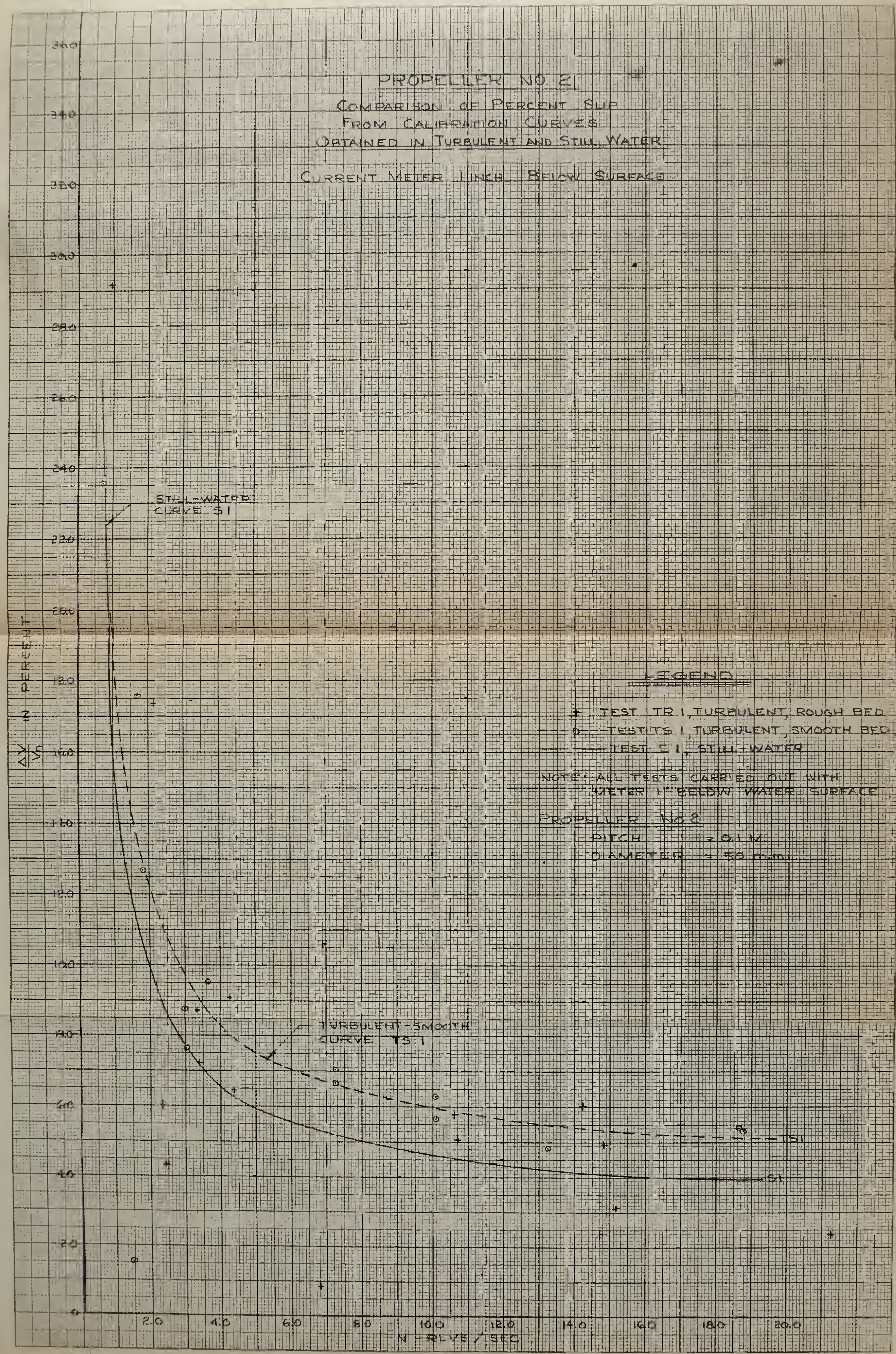

PROPELLER NO. 21
COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATER
CURRENT METER 1 INCH BELOW SURFACE
STILL-WATER CURVE S1
TURBULENT-SMOOTH CURVE TS1
LEGEND
+ TEST TR1, TURBULENT, ROUGH BED
o TEST TS1, TURBULENT, SMOOTH BED
TEST S1, STILL-WATER
NOTE: ALL TESTS CARRIED OUT WITH METER 1" BELOW WATER SURFACE
PROPELLER No 2
PITCH = 0.1 M.
DIAMETER = 50 mm.
$\frac{\Delta V}{V_c}$ IN PERCENT
N - REVS / SEC
TS1
S1

FIGURE 13

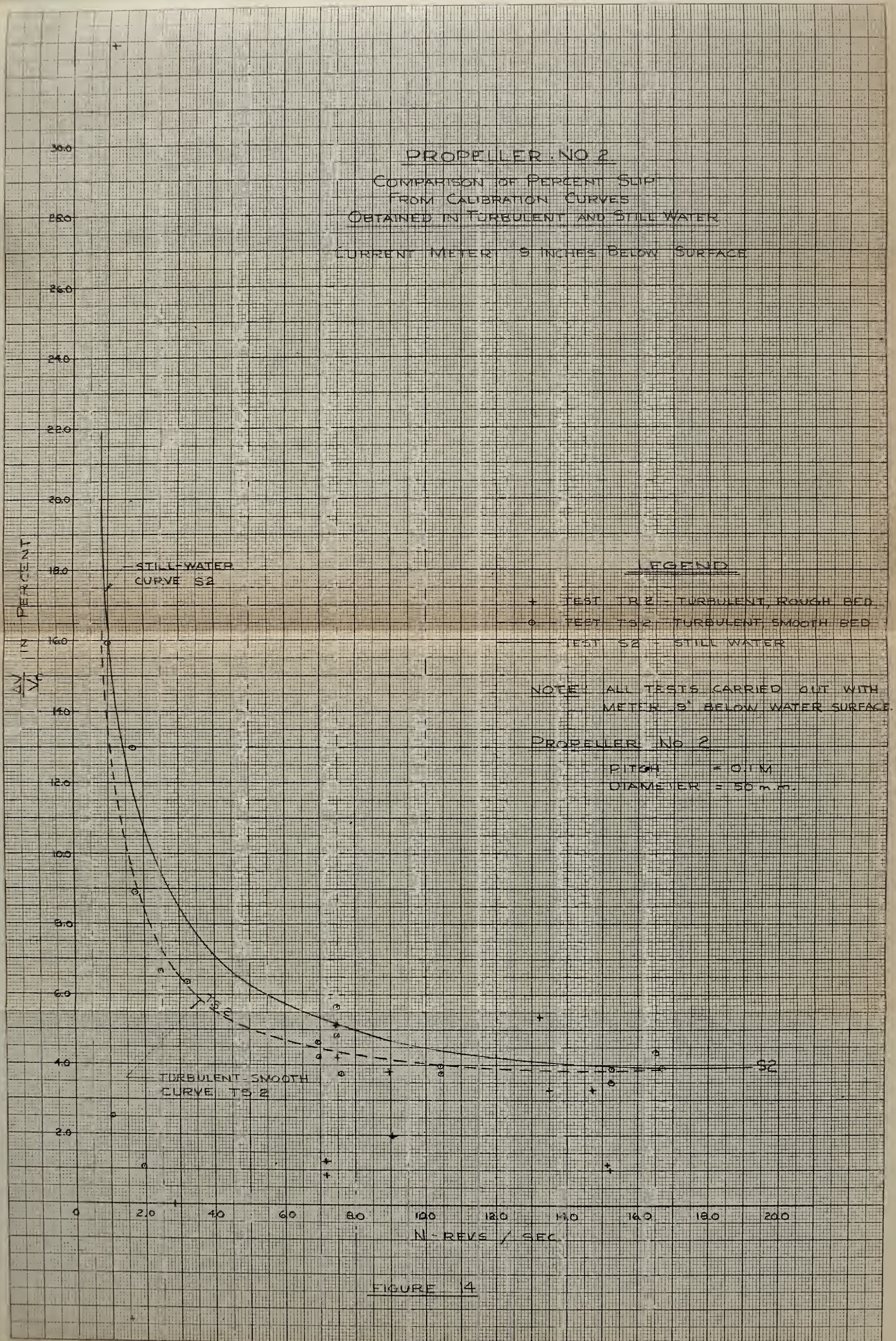

PROPELLER NO 2
COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATER
CURRENT METER 9 INCHES BELOW SURFACE
LEGEND
+ TEST TR 2 - TURBULENT, ROUGH BED
o TEST TS 2 - TURBULENT, SMOOTH BED
TEST S2 - STILL WATER
NOTE: ALL TESTS CARRIED OUT WITH METER 9" BELOW WATER SURFACE.
PROPELLER NO 2
PITCH = 0.1 M
DIAMETER = 50 m.m.
STILL-WATER CURVE S2
TURBULENT SMOOTH CURVE TS 2
TS2
S2
$\frac{\Delta V}{V_c}$ IN PERCENT
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
N - REVS / SEC.

FIGURE 14

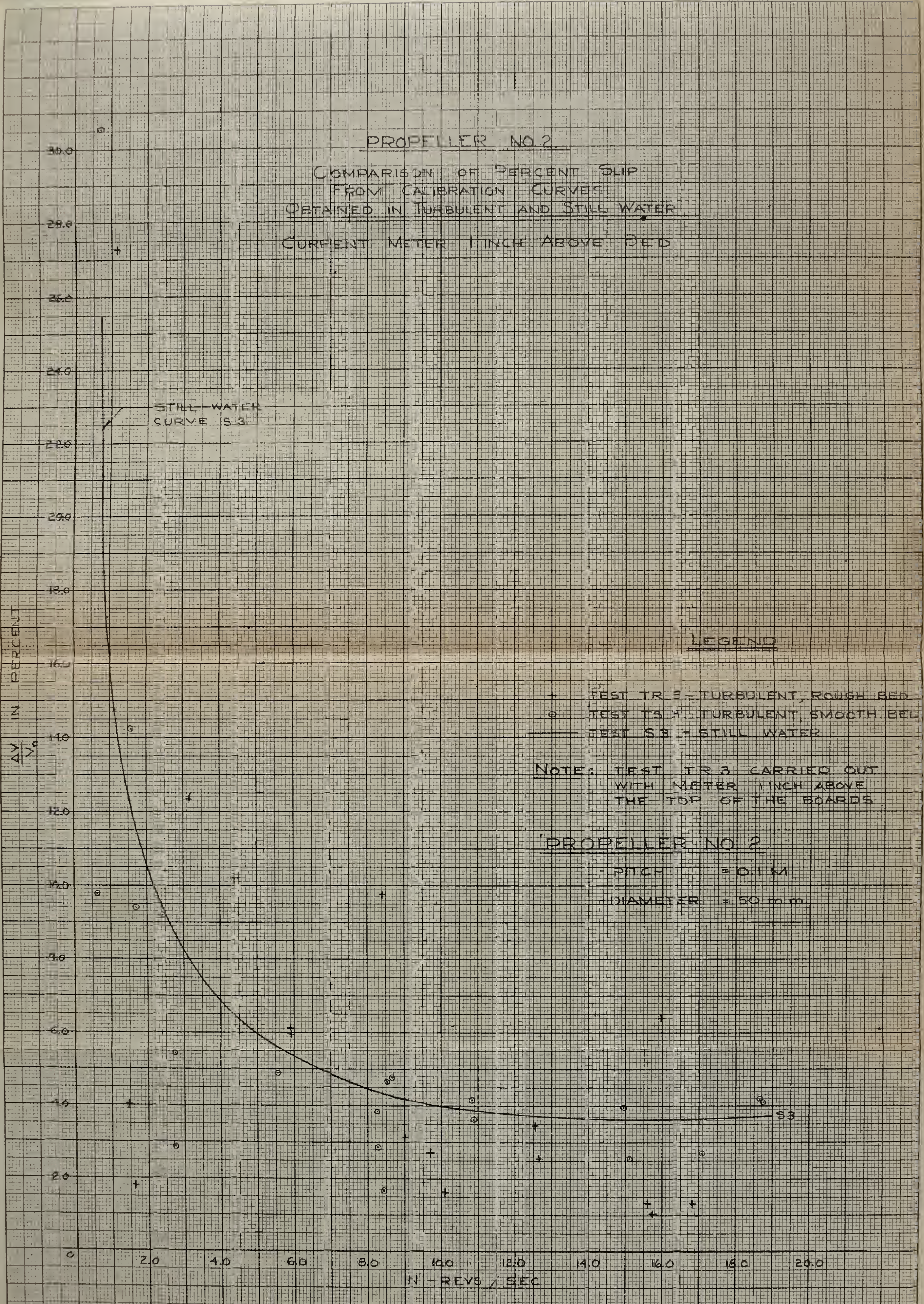

PROPELLER NO. 2.
COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATER
CURRENT METER 1 INCH ABOVE BED
STILL WATER CURVE S 3.
LEGEND
+ TEST TR 3 - TURBULENT, ROUGH BED
⊙ TEST TS 3 - TURBULENT, SMOOTH BED
—— TEST S 3 - STILL WATER
NOTE: TEST TR 3 CARRIED OUT WITH METER 1 INCH ABOVE THE TOP OF THE BOARDS.
PROPELLER NO. 2
PITCH = 0.1 M
DIAMETER = 50 m.m.
S 3
ΔV/V₀ IN PERCENT
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
N - REVS / SEC

FIGURE 15

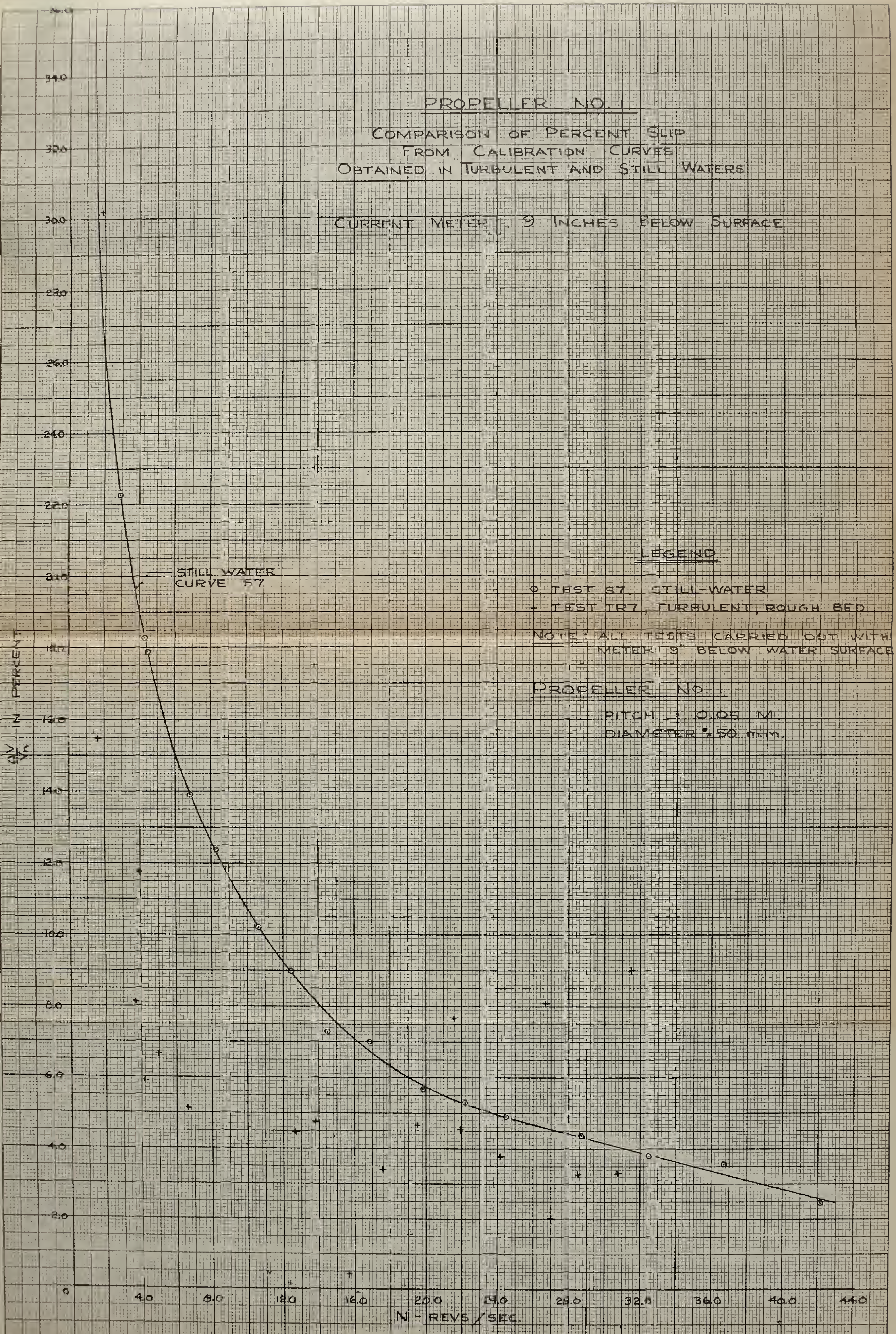

PROPELLER NO. I
COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATERS
CURRENT METER 9 INCHES BELOW SURFACE
LEGEND
⊙ TEST S7, STILL-WATER
+ TEST TR7, TURBULENT, ROUGH BED
NOTE: ALL TESTS CARRIED OUT WITH METER 9" BELOW WATER SURFACE.
PROPELLER NO. I
PITCH : 0.05 M.
DIAMETER : 50 mm.
STILL WATER CURVE S7
$\frac{\Delta V}{V_c}$ IN PERCENT
N - REVS./SEC.
0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
2.0
6.0
10.0
14.0
18.0
22.0
26.0
30.0
34.0

FIGURE 16

PROPELLER NO 2

COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATERS

CURRENT METER 9 INCHES BELOW SURFACE

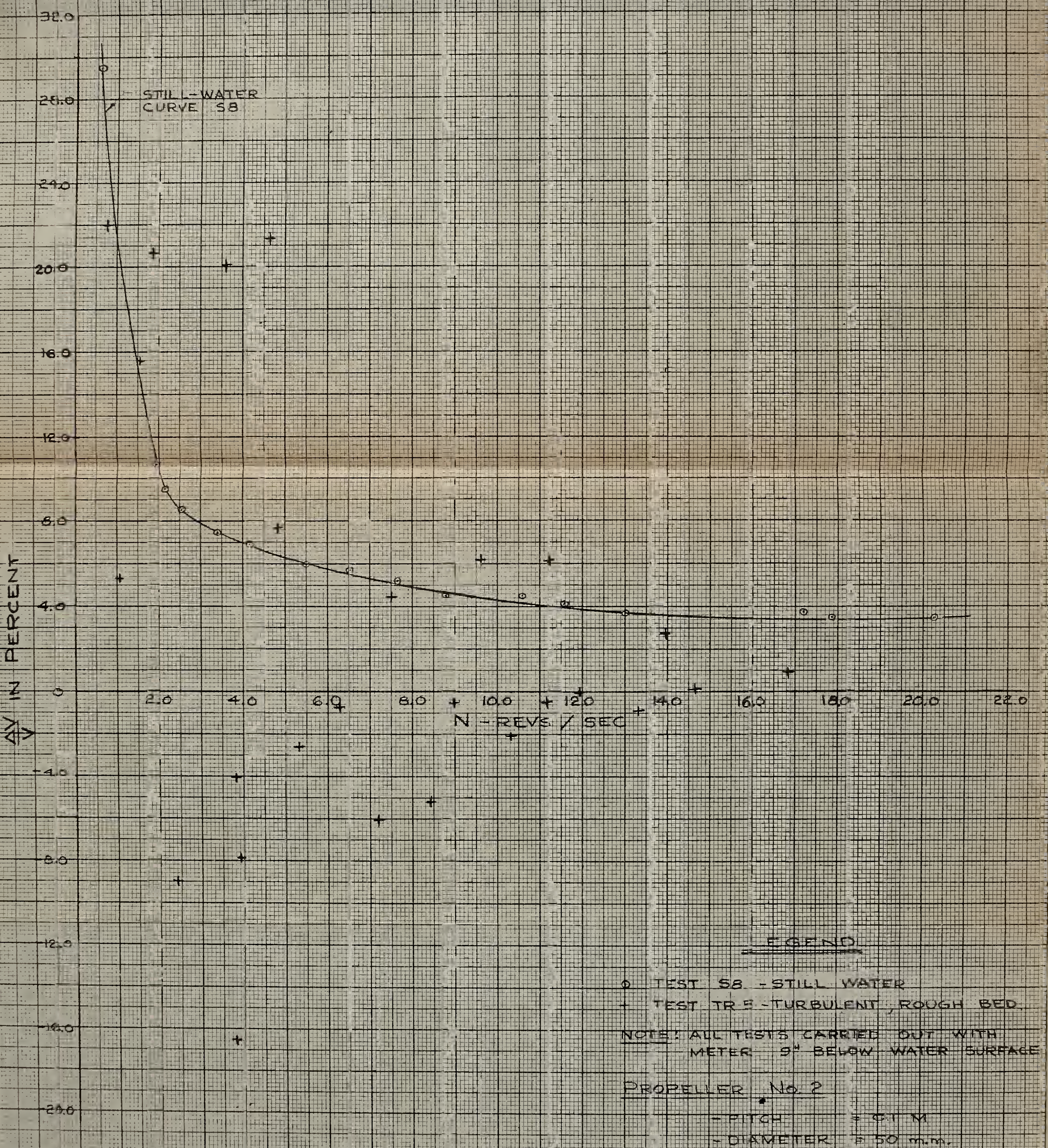


FIGURE 17

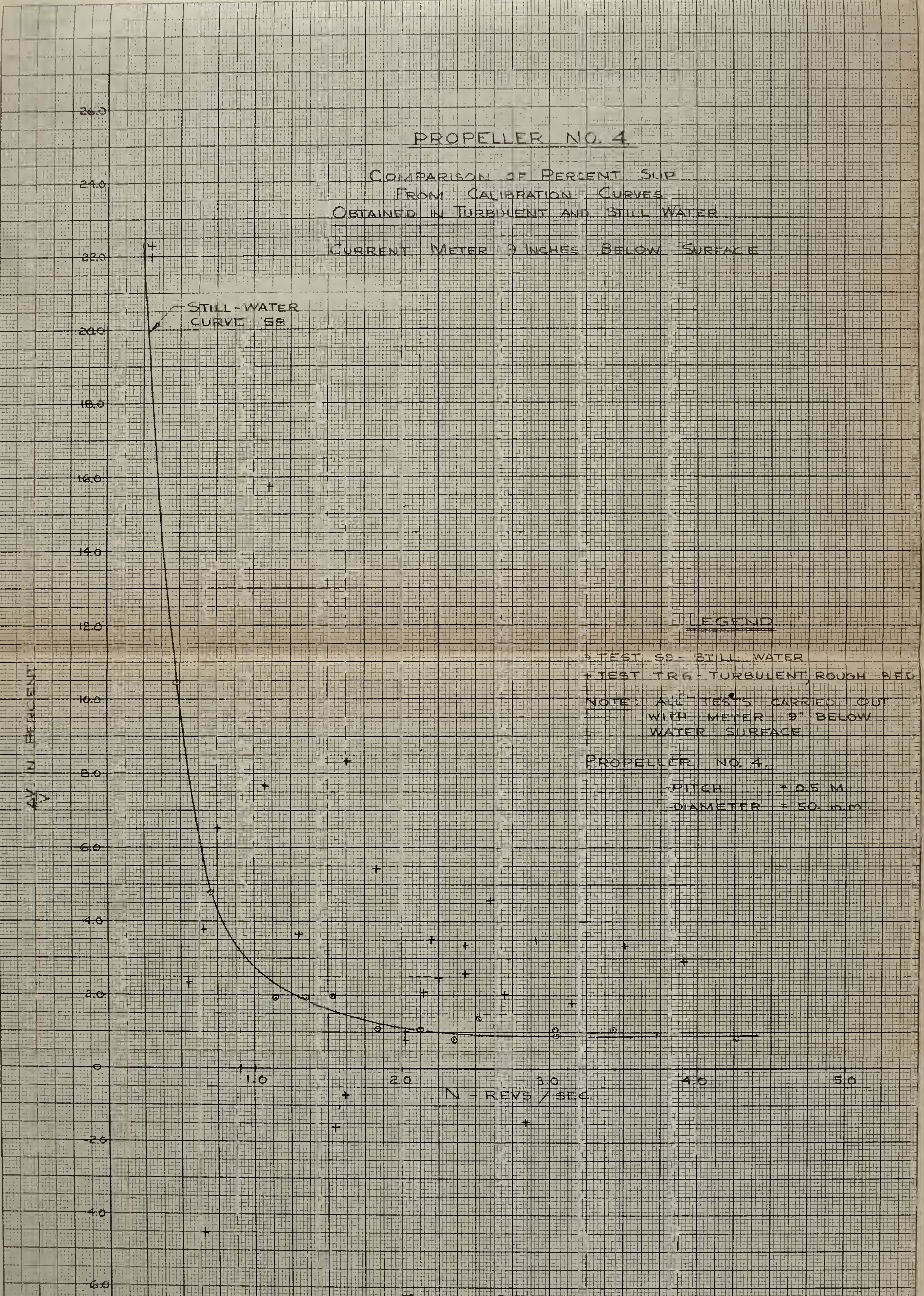

PROPELLER NO. 4
COMPARISON OF PERCENT SLIP
FROM CALIBRATION CURVES
OBTAINED IN TURBULENT AND STILL WATER
CURRENT METER 9 INCHES BELOW SURFACE
STILL-WATER CURVE S8
LEGEND
○ TEST S9 - STILL WATER
+ TEST TR6 - TURBULENT, ROUGH BED
NOTE: ALL TESTS CARRIED OUT WITH METER 9" BELOW WATER SURFACE
PROPELLER NO. 4.
PITCH = 0.5 M
DIAMETER = 50 m.m
ΔV/V IN PERCENT
N - REVS / SEC.
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
-2.0
-4.0
-6.0
1.0
2.0
3.0
4.0
5.0

FIGURE 18

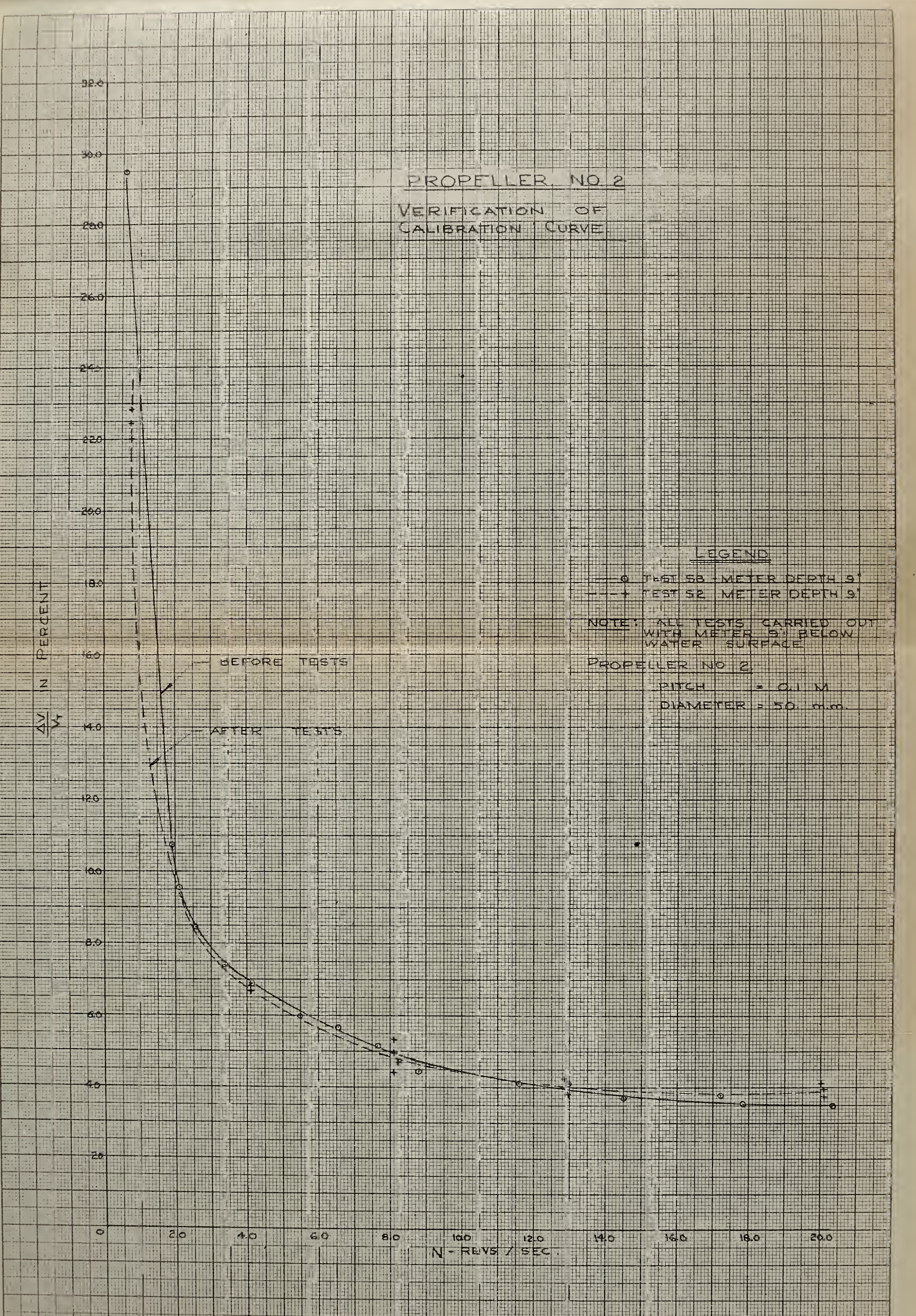

PROPELLER NO 2
VERIFICATION OF
CALIBRATION CURVE
LEGEND
TEST 58 METER DEPTH 9'
TEST 52 METER DEPTH 9'
NOTE: ALL TESTS CARRIED OUT WITH METER 9' BELOW WATER SURFACE
PROPELLER NO 2
PITCH = 0.1 M
DIAMETER = 50 m.m.
BEFORE TESTS
AFTER TESTS
$\frac{\Delta V}{V_T}$ IN PERCENT
N - REVS / SEC.
0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0

FIGURE 19

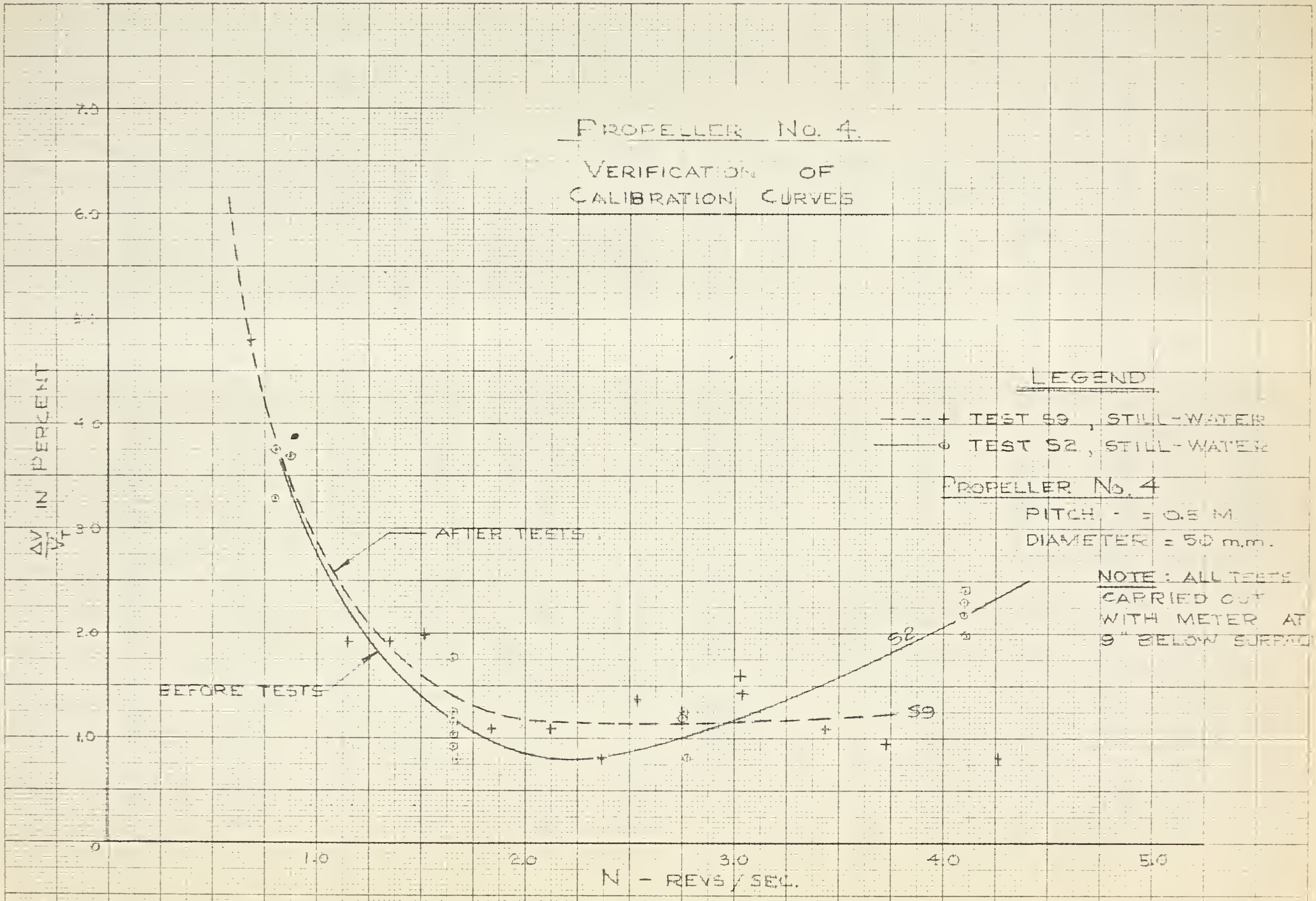

PROPELLER No. 4.
VERIFICATION OF
CALIBRATION CURVES
LEGEND
TEST 59, STILL-WATER
TEST 52, STILL-WATER
PROPELLER No. 4
PITCH - = 0.5 M
DIAMETER = 50 m.m.
NOTE: ALL TESTS CARRIED OUT WITH METER AT 9" BELOW SURFACE
AFTER TESTS
BEFORE TESTS
52
59
ΔV/V IN PERCENT
7.0
6.0
4.0
3.0
2.0
1.0
0
1.0
2.0
3.0
4.0
5.0
N - REVS / SEC.

FIGURE 20

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APPENDIX A

EXPERIMENTS USING THE PHOTOGRAPHIC TECHNIQUE FOR MEASURING TURBULENCE

1. PURPOSE AND SCOPE

The lack of a hot-film anemometer resulted in an attempt being made to measure the turbulence present in the flow using photographic methods. In this method, immiscible droplets of the same density as water are injected into the flow to make the flow paths visible. The paths of the droplets are recorded photographically. By knowing the exposure time and length of the streak, flow velocities are determined. This method is only applicable to laboratory flumes having transparent windows or sides.

Various mixtures were tried for forming the immiscible droplets. The size of droplet was varied by changing the injecting apparatus. Both still and movie cameras were tried with various types of lighting.

Although no useful results were recorded, considerable experience was obtained with the required techniques.

2. THEORY

The velocity at an instant can be described by rectangular components U, V, and W, U being in the direction of mean flow and V, W, perpendicular to U. The instantaneous velocity U can be represented by:

$$U = \overline{U} + u'$$

$\overline{U}$ is the mean axial velocity with respect to time at any point and u' is the fluctuating part due to turbulence. Since the mean flow is in the direction of $\overline{U}$, then $\overline{V}$, $\overline{W}$ are zero. The

turbulence components in the V, W directions, at any instant, are v' and w'.

By obtaining the trace of a droplet in the flow with the axis of the camera being perpendicular to the flow, (in the same direction as the component V or W), the value of U can be determined. Figure 21 is an example.

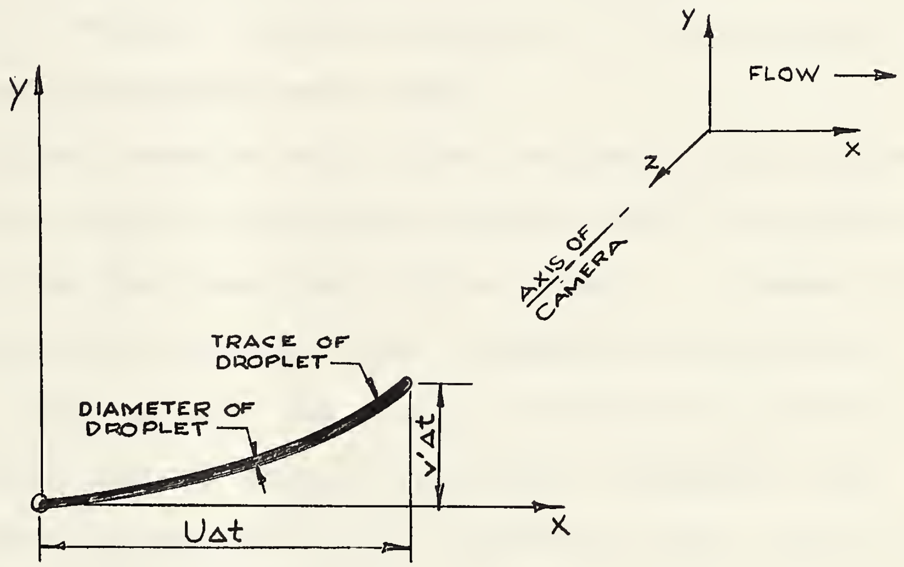

Figure 21

Determination of Turbulent Components

Three measurements per streak are necessary: the components, ($U\Delta t$, $v'\Delta t$), along and perpendicular to the conduit, and the streak width. As the exposure times (Δt) are known, these are then used in the following manner:

$\frac{1}{\Delta t}$. (Projected Streak Length - Streak Width (droplet size))

= Velocity Component in that direction at that instant.

The mean of these lengths gives the mean velocity at that point

$(\bar{U})$. Subtracting the individual velocity values at various instances from the mean, gives u'.

Similarly, with the axis of the camera in the y-direction, the values of w' can be determined.

Reference 17 discusses this method in detail.

3. APPARATUS

The flume used was the one outlined in Section 4.1. Windows of clear plastic, 22 inches wide by 46 inches long were located at various intervals along it. It was through one of these the photographs were taken.

Various cameras were tried: an Asahi Pentax, Model H2; a Bell and Howell, 16 mm Movie Camera, Model 70-H; and a DES-200-P, 16 mm Bell and Howell Pulse Camera. A number of different lenses and extension tube arrangements were used. The extension tubes allowed the camera to be set very close to the window when used in conjunction with a telephoto lens.

Both a carbon arc lamp, and movie light, manufactured under the trade name "Sun Gun", were used. The Sun Gun uses a small quartz lamp containing a Halogen compound. An adjustable slit was placed between the light source and water. This produced a flat band of light.

4. EXPERIMENTAL PROCEDURES

(a) Immiscible Droplet Mixture

The first step in this investigation was to develop a mixture of petroleum products that would form immiscible droplets in water. A number of combinations will work; to name a few: Carbon Tetrachloride and Benzine; Kerosene and Dibutyl Phthalate; Petroleum Ether and Dichloroethane; Dichloroethane

and a viscous mineral oil sold under the trade name of "Primal D"; and Kerosene and Dichloroethane. Of the above, both the Primal D or Kerosene mixed with Dichloroethane were found to be most suitable. The others, although useable, were either too volatile, highly inflammable or difficult to contain.

(b) Method of Injecting Droplets

The injector used to introduce the droplets into the flow was a piece of 1/4 inch copper tubing. The bottom end was bent at 90 degrees and a standard hypodermic fitting was attached. This allowed the needles to be installed and removed easily. No attempt was made to streamline the injector. A simple pressure system was installed by using mainline water pressure as shown in Figure 22.

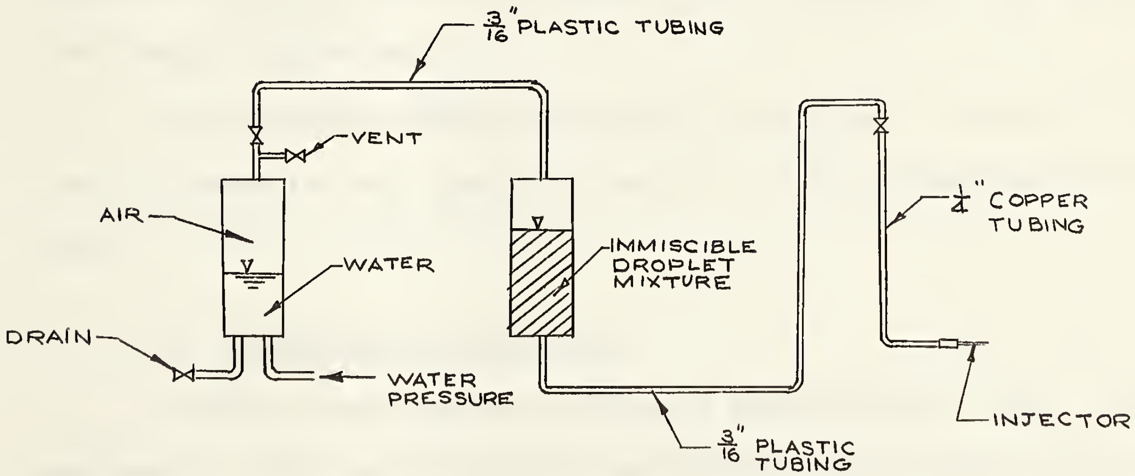

Figure 22

Pressure System for Injector

By opening and closing the drain valve the pressure on the mixture could be regulated.

The droplet size could be reduced by using smaller sized hypodermic needles or by increasing the pressure. The amount of droplets could also be varied in this manner. For the Kerosene and Dichloroethane mixture, a No. 22 needle gave good results, requiring very little additional pressure. To produce similar results with the Primal D and Dichloroethane mixture, a No. 20 needle was used and more pressure applied.

The faster the flow, the easier it was to keep the droplets small. This was due to the drops being washed off the end of the needle before they could attain any size.

(c) Sizes of Droplets

The size of droplet used was approximately 2 mm in diameter. This could easily be varied by changing the mixture, needle size, or pressure. Generally, the higher the viscosity the larger the drops.

Innumerable combinations were tried but the size of needle and the mixture were governed mainly by the coloring substance used.

(d) Coloring of Droplets

In this investigation "Streak Photography", Ref. 18, 19), was used. This entailed photographing the droplets against a black background. To do this, a white coloring was added to the droplet mixture. Zinc Oxide, Titanium Oxide, powdered Aluminum, powdered Anthracene and Aluminum Paint were all tried. All except the last were unsatisfactory, either plugging up the injector or requiring too large a needle for the size of drop

wanted. The aluminum paint was fine enough to pass through a small needle, and did not settle out rapidly. The paint was added in limited amounts. Too much resulted in only the top half of the drops being illuminated.

(e) Lighting

The droplets were illuminated by lamps located over the top of the flume. With the exception of these lamps, the room was completely dark. Two methods of lighting were tried: carbon arc, and movie lights (Sun Gun). An adjustable slip was placed between the water and lights (Figure 23).

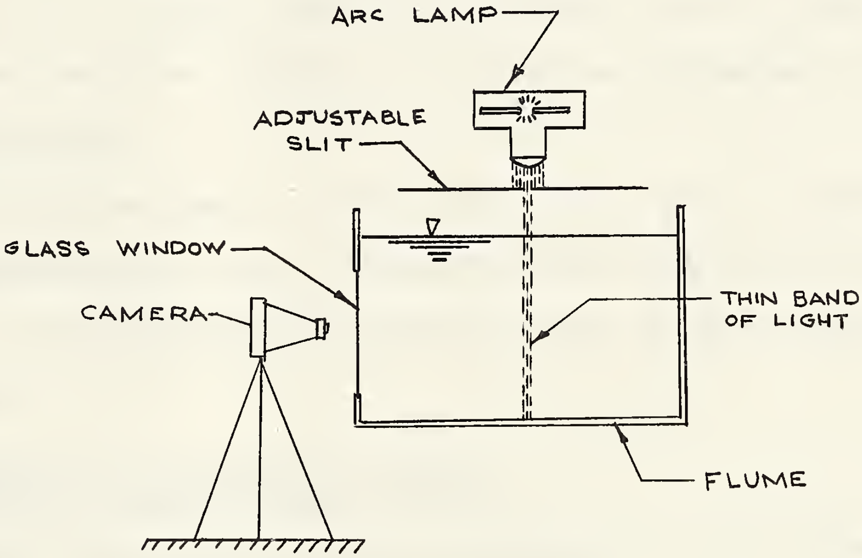

Figure 23

Arrangement of Apparatus

(i) Arc Lamp. The arc lamp with a focusing lens produced a narrow band of light about 3 inches wide and varying in thickness from 1/4 inch at the slip, to 1/2 inch at the floor of the flume.

This method is advantageous as only those droplets are seen which are in the narrow band. This allows the observation points to be changed by just moving the light beam. The injecting apparatus may also be located far enough upstream so that it does not affect the behavior of the drops.

(ii) Movie Lights (Sun Guns). Manufactured under the trade name "Sun Gun", these lights give a very brilliant light. Both one and two Sun Guns were used. They were located two feet above the water surface. Due to the type of reflector on these lamps, a wide area of the water was illuminated even though the slip was used. With lighting of this type, the injector would have to be located 3 or 4 inches upstream from the field of view of the camera so that the location at which the photograph was taken would be known.

A disadvantage was found with this type of lighting, in that the wider the area illuminated the cleaner the water has to be. Any foreign matter present gives a cloudy appearance to the water.

5. GENERAL PROCEDURE AND RESULTS

The camera was set up perpendicular to the flume. A transparent grid was photographed against a white background at the point in the water at which results were being obtained. This establishes what full size should be when the results are analysed. These tests being preliminary, recording the directions of the coordinate axes on each photograph was not considered.

The drops were photographed against a black background with the room in total darkness except for the light produced by the arc lamp or Sun Guns. Since the conditions to produce traces

were being sought, the exposure and lighting conditions were changed. The aperture was set on its lowest value. Both still pictures and moving pictures were taken.

Camera speeds varied from 1/4 to 1/100 of a second. The intention was to obtain a streak in the order of 3/4 inch in length at full size, as used by other investigators, (Ref. 17). The camera speeds will therefore vary with the flow velocity.

When the arc lamp was used with .35 mm Kodak Plus X film, streaks were recorded but only at very low velocities. At higher velocities only a slight blur, or, as in most cases, nothing at all was recorded. Both the Bell and Howell Pulse and Movie Cameras were tried using Ansco Super Hypan Film. Any results at low flows became blurred when blown up to actual size, this probably being due to the size of the negative as well as the poor photograph.

6. DISCUSSION

The use of the photographic method for determining the degree of turbulence present in the flow is both tedious and time consuming as admitted by most users. Investigations in which it was used have been carried out on very small scales; the largest in the literature reviewed being on a 10 1/2 inch wide by 10 inch deep closed conduit (Ref. 20). The number of photographs necessary for determining the mean velocity makes it necessary for them to be taken in rapid succession. The reliability of the results will depend to a great degree on the calibration of the camera's shutter opening. Reference 19 discusses various methods for establishing reliable exposure times.

Although the experiments produced no useful results, it

did point out the great number of the difficulties encountered in using this method. In addition to the problems which arose, others could arise in the calibrating of the camera and establishing the coordinate axes on the photographs. The latter is required to obtain the necessary components of velocity.

By using a very intense, and expensive, flashing light source it is probable that useable results can be obtained without the necessity of calibrating the camera lens. There is apparently no means of circumventing the lengthy task of analysing the photographs.

APPENDIX B

TEST NO. S1

PROPELLER NO. 2 ; PITCH K = 0.3281′ CURRENT METER DEPTH = 1″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	ΔV $V_T - KN$
1	72.53	94.5	23.[illegible]	0.7676	0.2518	0.3148	0.0630
2	73.33	[illegible]		0.7763	0.2547	0.3152	0.0605
3	73.5	95.20		0.7684	0.2521	0.3127	0.0606
4	85.20	[illegible]	"	4.1765	1.3702	1.4594	0.0892
5	85.22	20.3[illegible]	"	4.1918	1.37[illegible]	1.4644	0.0891
6	85.33	20.38	"	4.1869	1.3727	1.4608	0.0871
7	85.8[illegible]	10.40	"	[illegible].2500	2.7067	2.8626	0.1559
8	85.78	10.[illegible]	"	[illegible].25[illegible]0	2.7067	2.8654	0.1557
9	85.[illegible]	10.[illegible]		8.2356	2.7020	2.8626	0.1[illegible]
10	[illegible]	[illegible]		8.2613	2.7104	2.8598	0.1494
11	86.[illegible]	[illegible]	"	8.2613	2.7104	2.8598	0.14[illegible]
12	86.93	6.4[illegible]	"	13.5[illegible]	4.4510	4.6445	0.[illegible]26
13	87.0[illegible]	6.40		13.5938	4.4539	4.6517	0.1[illegible]
14	87.[illegible]	6.42	"	13.5514	4.44[illegible]	4.6372	0.[illegible]12
15	87.[illegible]	6.41	"	13.5725	4.4529	4.6444	0.19[illegible]5
16	87.10	4.33	"	20.1155	6.5995	6.8755	0.2760
17	87.00	4.32		20.1389	6.6072	6.8914	0.2842
18	87.00	4.33	"	20.0924	6.5920	6.8755	0.2835
19	87.20	4.34		20.0922	6.5919	6.8597	0.2678

EQUATION OF REGRESSION LINE $V = 0.3392\ N + 0.0516$

TEST NO. 52

PROPELLER NO. 2 ; PITCH K = 0.3281′   CURRENT METER DEPTH = 9″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW. VEL. FT./SEC.	$V_T - KN$ ΔV
1	70.00	92.10	29.771	0.7600	0.2494	0.3232	0.0738
2	70.37	92.80	"	0.7583	0.2488	0.3208	0.0720
3	70.78	92.48	"	0.7654	0.2511	0.3219	0.0708
4	70.83	93.00	"	0.7616	0.2499	0.3201	0.0702
5	84.56	20.68	"	4.0890	1.3415	1.4396	0.0981
6	84.56	20.69	"	4.0870	1.3409	1.4369	0.0980
7	84.67	20.70	"	4.0903	1.3420	1.4382	0.0962
8	85.90	10.60	"	8.1038	2.6587	2.8086	0.1499
9	86.25	10.59	"	8.1445	2.6721	2.8112	0.1391
10	86.75	10.62	"	8.1685	2.6800	2.8033	0.1233
11	86.50	10.59	"	8.1680	2.6798	2.8112	0.1314
12	86.50	10.58	"	8.1758	2.6823	2.8139	0.1316
13	86.54	10.57	"	8.1873	2.6861	2.8166	0.1305
14	87.27	6.74	"	12.9481	4.2480	4.4171	0.1691
15	86.87	6.73	"	12.9079	4.2349	4.4236	0.1887
16	86.93	6.76	"	12.8595	4.2190	4.4040	0.1850
17	87.[illegible]	4.34	"	20.0461	6.5768	6.8597	0.2829
18	87.17	4.[illegible]	"	20.1732	6.6201	6.8914	0.2713
19	87.35	4.32	"	20.2193	6.6338	6.8914	0.2576
20	87.10	4.34	"	20.0691	6.5843	6.8597	0.2754

EQUATION OF REGRESSION LINE $V = 0.3384\,N + 0.0557$

TEST NO. 53

PROPELLER NO. 2 ; PITCH K = 0.3281′ CURRENT METER DEPTH = 17″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	REVS. / SEC. (N)	FT. / SEC. (KN)	TOW. VEL. FT. / SEC.	ΔV $V_T - KN$
1	66.64	103.26	29.771	0.6454	0.2117	0.2883	0.0766
2	66.70	105.30	"	0.6334	0.2078	0.2827	0.0749
3	66.87	105.04	"	0.6366	0.2089	0.2834	0.0745
4	84.78	20.02	"	4.2348	1.3894	1.4871	0.0977
5	85.00	19.35	"	4.2607	1.3978	1.4923	0.0945
6	[illegible]	19.83	"	4.2789	1.4038	1.5013	0.0975
7	[illegible]	10.36	"	8.3890	2.7523	2.8736	0.1213
8	86.75	10.38	"	8.3574	2.7419	2.8681	0.1262
9	[illegible]	10.50	"	8.2667	2.7122	2.8353	0.1231
10	87.40	6.25	"	13.9840	4.5879	4.7634	0.1755
11	87.57	6.31	"	13.8779	4.5531	4.7181	0.1650
12	87.40	6.30	"	13.8730	4.5515	4.7256	0.1741
13	87.40	4.37	"	20.0000	6.5617	6.8126	0.2509
14	87.45	4.37	"	20.0114	6.5654	6.8126	0.2472
15	87.45	4.37	"	20.0114	6.5654	6.8126	0.2472

EQUATION OF REGRESSION LINE $V = 0.3369\,N + 0.0596$

TEST NO. S4

PROPELLER NO. 4 ; PITCH K = 1.6404' CURRENT METER DEPTH = 1" ; WATER DEPTH = 18"

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	ΔV V_T - KN
1	17.46	19.78	29.771	0.8827	1.4480	1.5051	0.0571
2	17.50	19.80	"	0.8838	1.4499	1.5036	0.0537
3	17.50	19.82	"	0.8830	1.4484	1.5021	0.0537
4	17.73	10.73	"	1.6524	2.7106	2.7746	0.0640
5	17.73	10.70	"	1.6570	2.7182	2.7823	0.0641
6	17.77	10.74	"	1.6546	2.7142	2.7720	0.0578
7	17.71	10.70	"	1.6551	2.7151	2.7823	0.0672
8	17.73	10.70	"	1.6570	2.7182	2.7823	0.0641
9	17.77	10.71	"	1.6592	2.7218	2.7797	0.0579
10	17.79	10.73	"	1.6580	2.7197	2.7746	0.0549
11	17.73	10.71	"	1.6555	2.7156	2.7797	0.0641
12	17.72	10.70	"	1.6561	2.7166	2.7823	0.0657
13	17.74	10.72	"	1.6549	2.7146	2.7771	0.0625
14	17.73	10.72	"	1.6539	2.7131	2.7771	0.0640
15	17.85	10.73	"	1.6636	2.7289	2.7746	0.0457
16	17.75	10.72	"	1.6558	2.7162	2.7771	0.0609
17	17.79	10.76	"	1.6533	2.7122	2.7668	0.0546
18	17.69	10.70	"	1.6533	2.7120	2.7823	0.0703
19	17.77	10.74	"	1.6546	2.7142	2.7720	0.0578
20	17.83	10.70	"	1.6664	2.7335	2.7823	0.0488
21	17.79	10.72	"	1.6595	2.7223	2.7771	0.0548
22	17.74	10.70	"	1.6579	2.7197	2.7823	0.0626
23	17.83	10.74	"	1.6601	2.7233	2.7720	0.0487
24	17.83	6.53	"	2.7305	4.4791	4.5591	0.0800

EQUATION OF REGRESSION LINE $\acute{V}$ = 1.6650 N + .00199

TEST NO. 54

PROPELLER NO. 4 ; PITCH K = 1.6404′ CURRENT METER DEPTH = 1″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	$\overset{N}{\text{REVS./SEC.}}$	$\overset{KN}{\text{FT./SEC.}}$	TOW VEL. FT./SEC.	$\overset{\Delta V}{V_T - KN}$
25	17.90	6.55	29.771	2.7328	4.4830	4.5452	0.0622
26	17.89	6.55	"	2.7313	4.4804	4.5452	0.0648
27	17.83	4.33	"	4.1178	6.7549	6.8755	0.1206
28	17.81	4.35	"	4.0943	6.7163	6.8439	0.1276
29	17.75	4.35	"	4.0805	6.6936	6.8439	0.1503

EQUATION OF REGRESSION LINE V = 1.6650 N + 0.0199

TEST NO. S5

PROPELLER NO. 4 ; PITCH K = 1.6404′ CURRENT METER DEPTH = 9″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW. VEL. FT./SEC.	ΔV V_T − KN
1	17.48	21.70	29.771	0.8055	1.3214	1.3719	0.0505
2	17.55	21.65	"	0.9106	1.3293	1.3751	0.0453
3	17.47	21.62	"	0.8081	1.3255	1.3770	0.0515
4	17.83	10.78	"	1.6540	2.7132	2.7617	0.0485
5	17.96	10.78	"	1.6660	2.7330	2.7617	0.0287
6	17.98	10.79	"	1.6664	2.7335	2.7591	0.0256
7	17.92	10.79	"	1.6608	2.7244	2.7591	0.0347
8	18.00	10.75	"	1.6744	2.7467	2.7694	0.0227
9	17.94	10.77	"	1.6657	2.7325	2.7643	0.0318
10	17.98	10.74	"	1.6741	2.7462	2.7720	0.0258
11	18.00	10.78	"	1.6698	2.7391	2.7617	0.0226
12	17.92	10.72	"	1.6716	2.7422	2.7771	0.0349
13	17.97	10.72	"	1.6763	2.7498	2.7771	0.0273
14	17.92	6.48	"	2.7654	4.5364	4.5943	0.0579
15	18.00	6.48	"	2.7778	4.5567	4.5943	0.0376
16	17.93	6.48	"	2.7670	4.5390	4.5943	0.0553
17	17.71	4.31	"	4.1090	6.7405	6.9074	0.1669
18	17.73	4.32	"	4.1042	6.7325	6.8914	0.1589
19	17.75	4.32	"	4.1058	6.7401	6.8914	0.1513
20	17.79	4.32	"	4.1181	6.7553	6.8914	0.1361

EQUATION OF REGRESSION LINE V = 1.6776 N + 0.0208

80

TEST NO. S6

PROPELLER NO. 4 ; PITCH K = 1.6404′   CURRENT METER DEPTH = 17″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW. VEL. FT./SEC.	ΔV V_T - KN
1	17.53	20.90	29.771	0.8388	1.3759	1.4244	0.0485
2	17.52	20.95	"	0.8363	1.3718	1.4211	0.0493
3	17.46	20.90	"	0.8354	1.3704	1.4244	0.0540
4	17.89	10.32	"	1.7335	2.8437	2.8848	0.0411
5	17.87	10.30	"	1.7350	[illegible]	2.8904	0.0444
6	17.87	10.32	"	1.7316	[illegible]	2.8848	[illegible]
7	18.00	6.42	"	2.8037	4.5993	4.6372	0.0379
8	18.10	6.41	"	2.8237	[illegible]	4.6445	0.0124
9	18.15	6.44	"	2.8183	[illegible]	[illegible]	-0.0004
10	17.91	4.32	"	4.1458	[illegible]	[illegible]	0.0905
11	18.00	4.33	"	4.1570	6.8193	6.8755	0.0562
12	17.83	4.32	"	4.1273	[illegible]	6.8914	0.1209

EQUATION OF REGRESSION LINE V = 1.6499 N + 0.0274

TEST NO. S7

PROPELLER NO. 1 ; PITCH K = 0.1640′ CURRENT METER DEPTH = 9″ ; WATER DEPTH = 18″ .

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	REVS./SEC. N	FT./SEC. KN	TOW VEL. FT./SEC.	ΔV V_T − KN
1	115.15	89.90	29.771	1.2809	0.2101	0.3312	0.1211
2	59.10	182.65	"	0.3236	0.0531	0.1630	0.1099
3	141.10	48.22	"	2.9262	0.4800	0.6174	0.1374
4	148.30	34.49	"	4.2998	0.7053	0.8632	0.1579
5	149.60	32.92	"	4.5261	0.7425	0.9043	0.1618
6	153.20	22.30	"	[illegible]8210	1.1189	1.3000	0.1311
[illegible]	159.00	19.41	"	8.1917	1.3438	1.5338	0.1900
8	163.00	15.32	"	10.6400	1.7453	1.9433	0.1980
9	165.20	13.28	"	12.440[illegible]	2.0406	2.2418	0.2012
10	168.25	11.53	"	14.5[illegible]	2.3834	2.5709	0.1675
11	168.75	10.02	"	16.84[illegible]	2.7627	2.9712	0.2085
12	171.20	8.63	"	19.8330	3.2542	3.4437	0.1955
[illegible]	171.75	7.71	"	22.2760	3.[illegible]	3.8613	0.2071
[illegible]	172.50	7.03	"	24.5330	4.0252	4.2349	0.2097
[illegible]	173.60	6.05	"	28.6940	4.7070	4.9206	0.2136
16	174.60	5.37	"	3[illegible].5140	5.3336	5.5439	0.2103
17	175.00	4.77	"	36.6[illegible]	6.0183	6.2413	0.2230
18	177.00	4.20	"	42.1[illegible]	6.9132	7.0883	0.1751

EQUATION OF REGRESSION LINE V = 0.1658 N + 0.1541

TEST NO. S8

PROPELLER NO. 2 ; PITCH K = 0.3281′ . CURRENT METER DEPTH = 3 ; WATER DEPTH = 8

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	ΔV V_T − KN
1	64.00	108.95	29.771	0.5874	0.1927	0.2733	0.0806
2	81.00	42.40	"	1.9104	0.6268	0.7022	0.0754
3	82.10	38.60	"	2.1269	0.6975	0.7713	0.0735
4	83.10	32.50	"	2.5569	0.8389	0.9160	0.0771
5	84.00	24.80	"	3.3871	1.1112	1.2004	0.0892
6	84.50	20.34	"	4.1544	1.3630	1.4637	0.1007
7	85.30	15.60	"	5.4679	1.7939	1.9084	0.1145
8	85.60	13.10	"	6.5344	2.1438	2.2726	0.1288
9	86.10	11.26	"	7.6465	2.5087	2.6440	0.1353
10	86.70	9.86	"	8.7921	2.8840	3.0184	0.1345
11	86.70	8.18	"	10.5990	3.4774	3.6395	0.1621
12	87.00	7.50	"	11.6000	3.8058	3.9695	0.1637
13	87.00	6.70	"	12.9850	4.2602	4.4434	0.1832
14	87.40	6.03	"	14.4940	4.7553	4.9371	0.1818
15	87.30	5.07	"	17.2190	5.6492	5.8720	0.2228
16	87.55	4.90	"	17.8670	5.8620	6.0757	0.2137
17	87.57	4.31	"	20.3180	6.6659	6.9074	0.2415

EQUATION OF REGRESSION LINE V = 0.3369 N + 0.0631

TEST NO. 59

PROPELLER NO. 4 ; PITCH K = 1.6404′ CURRENT METER DEPTH = 9″ ; WATER DEPTH = 18″

RUN NO.	PROP. REVS.	TIME IN SECS.	DISTANCE	REVS. ^{N}/ SEC.	FT. ^{KN}/ SEC.	TOW VEL. FT./ SEC.	$V_T - KN$ ΔV
1	8.75	89.00	29.771	0.0933	0.1613	0.3345	0.1732
2	14.10	56.90	"	0.2478	0.4065	0.5232	0.1167
3	16.25	33.80	"	0.4808	0.7887	0.8808	0.0921
4	17.28	24.10	"	0.7170	1.1762	1.2353	0.0591
5	17.80	15.55	"	1.1447	1.8778	1.9145	0.0367
6	17.80	13.17	"	1.3516	2.2171	2.2605	0.0434
7	17.83	11.70	"	1.5239	2.4999	2.2445	0.0446
8	17.95	9.77	"	1.8373	3.0139	3.0472	0.0333
9	17.95	8.47	"	2.1192	3.4764	3.5149	0.0385
10	18.00	7.62	"	2.3622	3.8750	3.9070	0.0320
11	17.90	7.06	"	2.5354	4.1591	4.2169	0.0578
12	17.95	5.92	"	3.0321	4.9739	5.0289	0.0550
13	17.98	5.91	"	3.0423	4.9906	5.0374	0.0468
14	17.95	5.23	"	3.4321	5.6301	5.6924	0.0623
15	17.98	4.82	"	3.7303	6.1192	6.1766	0.0574
16	18.0	4.22	"	4.2654	6.9970	7.0547	0.0577

EQUATION OF REGRESSION LINE $V = 1.6259\,N + 0.0918$

TEST NO. TS 1

Propeller No. 2 ; Pitch K = 0.3281' ; Current Meter Depth = 1" ; Water Depth = 18" ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs. / Sec.	KN Ft. / Sec.	Tow Vel. Ft. / Sec.	$V_n = \lvert V_w + V_T \rvert$ Ft. / Sec.	$V_n - KN$ Ft. / Sec.
1	D/S	303.00	- 83.00	29.771	3.6506	1.1977	-0.3587	1.3237	0.1260
2	D/S	148.30	- 49.00	"	3.0265	0.9930	-0.6076	1.0748	0.0818
3	D/S	146.20	- 48.95	"	2.9867	0.9799	- 0.6082	1.0742	0.0943
4	D/S	40.33	- 27.00	"	1.4937	0.4901	-1.1026	0.5798	0.0897
5	D/S	11.88	- 21.40	"	0.5514	0.1809	-1.3912	0.2912	0.1103
6	D/S	50.30	- 29.60	"	1.6993	0.5575	-1.0058	0.6766	0.1191
7	D/S	53.30	- 29.60	"	1.8007	0.5908	- 1.0058	0.6766	0.0858
8	D/S	15.30	- 21.60	"	0.7083	0.2324	-1.3783	0.3041	0.0717
9	D/S	12.30	- 21.60	"	0.5694	0.1868	-1.3783	0.3041	0.1173
10	U/S	244.80	33.67	"	7.2706	[illegible]	0.8842	2.5666	0.1813
11	U/S	245.80	33.67	"	7.3003	[illegible]	0.8842	2.5666	0.1715
12	U/S	163.30	16.06	"	10.1681	[illegible]	1.8537	3.5361	0.2001
13	U/S	162.20	16.06	"	10.0996	[illegible]	1.8537	3.5361	0.2226
14	U/S	136.60	10.30	"	13.2621	[illegible]	2.8904	4.5729	0.2217
15	U/S	136.60	10.30	"	13.2621	[illegible]	2.8904	4.5728	0.2217
16	U/S	116.00	6.22	"	[illegible]	6.1186	[illegible]	6.4687	0.3501
17	U/S	116.00	6.20	"	[illegible]	[illegible]	4.8018	6.4842	0.3459

Equation of Regression Line V = 0.3398 N + 0.0745

TEST NO. TS 1

PROPELLER NO. 2 ; PITCH K = 0.3281 ; CURRENT METER DEPTH = 1" ; WATER DEPTH = 18¼" ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS. / SEC.	KN FT. / SEC.	TOW VEL. FT. / SEC.	$V_n = \lvert V_w + V_T \rvert$ FT. / SEC.	$V_n - KN$ FT. / SEC.
18	D/S	12.30	-14.70	29.771	0.8367	0.2745	-2.0252	0.3428	0.0683
19	D/S	9.40	-15.10	"	0.6225	0.2042	-1.9716	0.2892	0.0850
20	D/S	49.50	- 7.40	"	6.6892	2.1946	-4.0231	2.3407	0.1461
21	D/S	49.60	- 7.40	"	6.7027	2.1990	-4.0231	2.3407	0.1417
22	D/S	50.00	- 7.40	"	6.7568	2.2168	-4.0231	2.3407	0.1239
23	D/S	65.10	- 4.36	"	14.9312	4.8987	-6.8282	5.1458	0.2471
24	D/S	66.00	- 4.36	"	15.1376	4.9664	-6.8282	5.1458	0.1794
25	D/S	66.00	- 4.34	"	15.2074	4.9893	-6.8597	5.1773	0.1880

EQUATION OF REGRESSION LINE V = 0.3398 N + 0.0745

TEST NO. TS 2

Propeller No. 2 ; Pitch K = 0.3281′; Current Meter Depth = 9 ; Water Depth = 18″ ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs./Sec.	KN Ft./Sec.	Tow Vel. Ft./Sec.	$V_n = \lvert V_w + V_T \rvert$ Ft./Sec.	V_n − KN Ft./Sec.
1	D/S	253.00	−78.80	29.771	3.2107	1.0534	−0.3778	1.1245	0.0711
2	D/S	113.50	−46.38	"	2.4472	0.8029	−0.6419	0.8604	0.0575
3	D/S	23.60	−25.95	"	0.9094	0.2984	−1.1472	0.3551	0.0567
4	D/S	27.60	−26.00	"	1.0615	0.3483	−1.1450	0.3573	0.0090
5	U/S	232.33	33.27	"	6.9832	2.2911	0.8948	2.3971	0.1060
6	U/S	231.70	33.24	"	6.9705	2.2869	0.8956	2.3979	0.1110
7	U/S	151.20	14.50	"	10.4276	3.4211	2.0532	3.5555	0.1344
8	U/S	150.65	14.44	"	10.4328	3.4228	2.0617	3.5640	0.1412
9	U/S	122.60	8.04	"	15.2490	5.0029	3.7029	5.2052	0.2023
10	U/S	123.00	8.02	"	15.3370	5.0317	3.7121	5.2144	0.1827

Equation of Regression Line $V = 0.3398\,N + 0.0272$

TEST NO. TS2

Propeller No. 2 ; Pitch K = 0.3281′; Current Meter Depth = 9″ ; Water Depth = 18″ ; Meter Facing D/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs./Sec.	KN Ft./Sec.	Tow Vel. Ft./Sec.	$V_n = \lvert V_W + V_T \rvert$ Ft./Sec.	V_n - KN Ft./Sec.
11	D/S	24.60	-13.92	29.771	1.7672	0.5738	-2.1387	0.6364	0.0566
12	D/S	23.50	-13.92	"	1.6882	0.5539	-2.1387	0.6364	0.0825
13	D/S	26.80	-13.90	"	1.9281	0.6326	-2.1418	0.6395	0.0069
14	D/S	54.30	- 7.25	"	7.4897	2.4572	-4.1063	2.6040	0.1465
15	D/S	54.70	- 7.26	"	7.5344	2.4719	-4.1007	2.5984	0.1265
16	D/S	55.40	- 7.25	"	7.6414	2.5070	-4.1063	2.6040	0.0970
17	D/S	68.70	- 4.13	"	16.6344	5.4575	-7.2085	5.7062	0.2487
18	D/S	69.00	- 4.13	"	16.7070	5.4813	-7.2085	5.7062	0.2249
19	D/S	69.00	- 4.14	"	16.6667	5.4681	-7.1911	5.6888	[illegible]

Equation of Regression Line V = 0.3398 N + 0.0272

TEST NO. TS 3

Propeller No. 2 ; Pitch K = 0.3281' ; Current Meter Depth = 17 ; Water Depth = 18" ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs./Sec.	KN Ft./Sec.	Tow Vel. Ft./Sec.	$V_n = \lvert V_w + V_T \rvert$ Ft./Sec.	$V_n - KN$ Ft./Sec.
1	D/S	168.10	-69.95	29.771	2.4031	0.7884	-0.4256	0.8682	0.0798
2	D/S	74.20	-43.80	"	1.6941	0.5558	-0.6797	0.6141	0.0583
3	D/S	70.67	-43.90	"	1.6098	0.5232	-0.6782	0.6157	0.0875
4	D/S	21.40	-30.82	"	0.6944	0.2278	-0.9660	0.3279	0.1001
5	D/S	19.00	-28.35	"	0.6702	0.2199	-1.0501	0.2437	0.0239
6.	U/S	266.14	47.94	"	5.5515	1.8214	0.6210	1.9148	0.0934
7	U/S	164.00	19.80	"	8.2828	2.7175	1.5036	2.7974	0.0799
8	U/S	162.00	19.70	"	8.2234	2.6979	1.5112	2.8051	0.1072
9	U/S	165.60	19.69	"	8.4104	2.7593	1.5120	2.8058	0.0465
10	U/S	134.40	12.35	"	10.8826	3.5704	2.4106	3.7044	0.1340
11	U/S	133.65	12.35	"	10.8219	3.5505	2.4106	3.7044	0.15[illegible]
12	U/S	118.65	7.85	"	15.1147	4.95[illegible]	3.7925	5.08[illegible]3	0.1274
13	U/S	116.90	7.84	"	14.9107	4.8[illegible]	3.7973	5.09[illegible]	0.1992
14	U/S	109.00	5.84	"	18.6644	6.1235	5.0978	6.3916	0.2681
15	U/S	109.00	5.82	"	18.7285	[illegible].1445	5.1153	6.[illegible]	0.2640

Equation of Regression Line V = 0.3372 N + 0.0390

TEST NO. TS3

PROPELLER NO. 2 ; PITCH K = 0.3281' ; CURRENT METER DEPTH = 17" ; WATER DEPTH = 18" ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	$V_n = \lvert V_W + V_T \rvert$ FT./SEC.	V_n - KN FT./SEC.
16	D/S	36.40	- 13.25	29.771	2.7472	0.9013	-2.2469	0.9530	0.0517
17	D/S	37.00	- 13.35	"	2.7715	0.9093	- 2.2300	0.9362	0.0269
18	D/S	60.10	- 7.03	"	8.5491	2.8048	- 4.2349	2.9410	0.1362
19	D/S	60.00	- 7.03	"	8.6771	2.8001	- 4.2349	2.9410	0.1409
20	D/S	72.10	- 4.22	"	17.0853	5.6054	- 7.0547	5.7609	0.1555
21	D/S	72.10	- 4.22	"	17.0853	5.6054	- 7.0547	5.7609	0.1555

EQUATION OF REGRESSION LINE $V = 0.3372\ N + 0.0390$

TEST NO. TR 1

PROPELLER No. 2 ; PITCH K = 0.3281′ ; CURRENT METER DEPTH = 1″ ; WATER DEPTH = 18 ; METER FACING U/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	$V_n = \lvert V_w + V_T \rvert$ FT./SEC.	V_n − KN FT./SEC.
1	D/S	198.50	− 46.33	29.771	4.2845	1.4057	−0.6426	1.5450	0.1403
2	D/S	202.55	− 46.13	"	4.3974	1.4427	−0.6454	1.5422	0.0995
3	D/S	100.60	− 30.14	"	3.3378	1.0951	−0.9878	1.1993	0.1042
4	D/S	102.33	− 30.15	"	3.3940	1.1135	−0.9874	1.2001	0.0866
5	D/S	51.80	− 21.88	"	2.3675	0.7767	−1.3606	0.8269	0.0502
6	D/S	53.40	− 21.90	"	2.4295	0.7971	−1.3545	0.8331	0.0360
7	D/S	15.40	− 15.81	"	1.1638	0.3818	−1.8830	0.3045	−0.0773
8	D/S	16.00	− 15.80	"	1.0127	0.3322	−1.8842	0.3033	−0.0289
9	D/S	20.67	− 15.80	"	1.3082	0.4292	−1.8842	0.3033	−0.1259
10	U/S	594.25	86.10	"	6.9019	2.2644	0.3458	2.5333	0.2689
11	U/S	211.00	19.72	"	10.6998	3.5104	1.5097	3.6972	0.1868
12	U/S	209.00	19.68	"	10.6199	3.4842	1.5128	3.7003	0.2161
13	U/S	153.00	10.08	"	15.1786	[illegible]	2.9535	5.1410	0.1612
14	U/S	150.00	10.06	"	14.9105	[illegible]	2.9593	5.1469	0.2550
15	U/S	127.20	5.93		21.4503	7.0375	5.0204	7.2080	0.1705

EQUATION OF REGRESSION LINE $V = 0.3398\ N + 0.0126$

TEST NO. TR1

Propeller No. 2 ; Pitch K = 0.3281' ; Current Meter Depth = 1" ; Water Depth = 18" ; Meter Facing D/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs. / Sec.	KN Ft. / Sec.	Tow Vel. Ft. / Sec.	$V_m = \lvert V_w + V_T \rvert$ Ft. / Sec.	$V_m - KN$ Ft. / Sec.
16	D/S	9.40	- 11.30	29.771	0.8319	0.2729	-2.6346	0.4470	0.1741
17	D/S	11.00	- 11.28	"	0.9752	0.3199	-2.6393	0.4517	0.1318
18	D/S	31.30	- 9.82	"	3.1874	1.0457	-3.0317	0.5441	-0.2016
19	D/S	26.30	- 9.76	"	2.6947	0.8341	-3.0503	0.0628	-0.0213
20	D/S	21.10	- 9.78	"	2.1575	0.7078	-3.0441	0.3565	0.1487
21	D/S	45.67	- 6.70	"	6.8164	2.2364	-4.4434	2.2559	0.0195
22	D/S	48.00	- 6.65	"	7.2180	2.3681	-4.4768	2.2893	-0.0788
23	D/S	61.50	- 4.16	"	14.7837	4.8503	-7.1565	4.9683	0.1196
24	D/S	59.20	- 4.16	"	14.2308	4.6689	-7.1565	4.9689	0.3000

Equation of Regression Line V = 0.3398 N + 0.0126

TEST NO. TR 2

Propeller No. 2 ; Pitch K = 0.3281' ; Current Meter Depth = 9" ; Water Depth = 18 ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs. / Sec.	KN Ft. / Sec.	Tow Vel. Ft. / Sec.	$V_n = \lvert V_w + V_T \rvert$ Ft. / Sec.	$V_n - KN$ Ft. / Sec.
1	D/S	140.70	-45.90	29.771	3.0654	1.0057	-0.6486	0.9124	-0.0933
2	D/S	131.70	-46.75	"	2.8171	0.9243	-0.6368	0.9242	-0.0001
3	D/S	25.50	-28.00	"	0.9107	0.2988	-1.0633	0.4978	0.1990
4	D/S	43.90	-28.00	"	1.5679	0.5144	-1.0633	0.4978	-0.0166
5	D/S	398.40	-98.20	"	4.0570	1.3310	-0.3032	1.2578	-0.0732
6	U/S	499.00	85.43	"	5.8410	1.9163	0.3485	1.9095	-0.0068
7	U/S	260.20	36.31	"	7.1661	2.3511	0.8199	2.3809	0.0298
8	U/S	261.20	36.30	"	7.1956	2.3608	0.8201	2.3811	0.0203
9	U/S	180.00	20.25	"	8.8889	2.9163	1.4702	3.0312	0.1149
10	U/S	183.33	20.24	"	9.0578	2.9717	1.4703	3.0319	0.0602
11	U/S	130.00	8.57	"	15.1692	4.9769	3.4739	5.0349	0.0581
12	U/S	130.25	8.58	"	15.1807	4.9805	3.4698	5.0308	0.0503
13	U/S	127.20	8.57	"	14.8425	4.8696	3.4739	5.0349	0.1653

Equation of Regression Line $V = 0.3368\ N - 0.0037$

TEST NO. TR2

PROPELLER NO. 2 ; PITCH K = 0.3281 ; CURRENT METER DEPTH = 9" ; WATER DEPTH = 18" ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS. / SEC.	KN FT. / SEC.	TOW VEL. FT. / SEC.	$V_n = \lvert V_w + V_T \rvert$ FT. / SEC.	V_n − KN FT. / SEC.
14	D/S	31.20	-14.10	29.771	2.2128	0.7260	-2.1114	0.5504	-0.1756
15	D/S	16.20	-14.00	"	1.1571	0.3796	-2.1265	0.5655	0.1859
16	D/S	53.50	-7.22	"	7.4100	2.4311	-4.1234	2.5624	0.1313
17	D/S	54.00	-7.22	"	7.4792	2.4538	-4.1234	2.5624	0.1086
18	D/S	64.10	-4.84	"	13.2438	4.3451	-6.1510	4.5900	0.2449
19	D/S	65.50	-4.84	"	13.5052	4.4400	-6.1510	4.5900	0.1500

EQUATION OF REGRESSION LINE $V = 0.3368\,N - 0.0037$

TEST NO. TR3

Propeller No. 2 ; Pitch K = 0.3281' ; Current Meter Depth = 14 7/8 ; Water Depth = 18 ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs./Sec.	KN Ft./Sec.	Tow Vel. Ft./Sec.	$V_n = \lvert V_W + V_T \rvert$ Ft./Sec.	$V_n - KN$ Ft./Sec.
1	D/S	133.10	-79.00	29.771	1.6848	0.5528	-0.3768	0.5363	-0.0165
2	D/S	129.55	-80.00	"	1.6194	0.5313	-0.3721	0.5410	0.0097
3	U/S	350.20	110.90	"	3.1578	1.0360	0.2684	1.1815	0.1455
4	U/S	153.00	25.85	"	5.9188	1.9418	1.1517	2.0648	0.1230
5	U/S	152.40	25.70	"	5.9300	1.9455	1.1534	2.0715	0.1260
6	U/S	125.50	13.95	"	8.9964	2.9516	2.1341	3.0472	0.0956
7	U/S	116.80	13.90	"	8.4029	2.7568	2.1418	3.0549	0.2981
8	U/S	111.50	8.88	"	12.5563	4.1195	3.3526	4.2657	0.1462
9	U/S	112.50	8.88	"	12.6680	4.1565	3.3526	4.2657	0.1092
10	U/S	107.00	6.36	"	16.8240	5.5196	4.6810	5.5941	0.0745
11	U/S	101.50	6.36	"	15.9591	5.2359	4.6810	5.5941	0.3582

Equation of Regression Line V = 0.3340 N + 0.0448

TEST NO. TR3

PROPELLER NO. 2 ; PITCH K = 0.3281'; CURRENT METER DEPTH = 14 7/8"; WATER DEPTH = 18 ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	$V_n = \lvert V_W + V_T \rvert$ FT./SEC.	$V_n - KN$ FT./SEC.
12	D/S	23.70	-20.90	29.771	1.1340	0.3720	-1.4244	0.5114	0.1394
13	D/S	31.00	-21.00	"	1.4762	0.4843	-1.4177	0.5046	0.02[illegible]3
14	D/S	52.00	-11.80	"	4.4068	1.4453	-2.5230	1.6099	[illegible]
15	D/S	61.20	-11.70	"	5.2308	1.7161	-2.5445	1.6314	-0.0847
16	D/S	57.00	-12.45	"	4.5783	1.5021	-2.3912	1.4781	-0.0240
17	D/S	69.00	-7.12	"	9.6910	3.1795	-4.1813	3.2682	0.0887
18	D/S	72.00	-7.14	"	10.0840	3.3084	-4.1696	3.2565	[illegible]
19	D/S	76.15	-4.88	"	15.6045	5.1196	-6.1006	5.[illegible]	0.5679
20	D/S	76.40	-4.86	"	15.7202	5.1575	-6.1257	[illegible]	0.0551

EQUATION OF REGRESSION LINE V = 0.3340 N + 0.0448

TEST NO. TR4

Propeller No. 1 ; Pitch K = 0.1640′; Current Meter Depth = 9″ ; Water Depth = 1.46′ ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs. / Sec.	KN Ft. / Sec.	Tow Vel. Ft. / Sec.	$V_n = \lvert V_W + V_T \rvert$ Ft. / Sec.	V_n − KN Ft. / Sec.
1	D/S	27.35	−16.40	29.771	1.6677	0.2736	−1.8153	0.3236	0.0500
2	D/S	16.77	−20.33	"	0.8249	0.1353	−1.4644	0.0273	−0.1080
3	D/S	87.33	−24.85	"	3.5143	0.5765	−1.1980	0.2937	−0.2828
4	D/S	53.85	−28.44	"	1.8935	0.3106	−1.0468	0.4449	0.1343
5	D/S	134.00	−36.00	"	3.7222	0.6106	−0.8270	0.6647	0.0541
6	D/S	217.50	−45.58	"	4.7718	0.7828	−0.6532	0.8385	0.0557
7	D/S	557.70	−84.60	"	6.5922	1.0814	−0.3519	1.1398	0.0584
8	U/S	943.30	84.26	"	11.1951	1.8364	0.2533	1.8450	0.0086
9	U/S	556.10	44.06	"	12.6214	2.0704	0.6757	2.1674	0.0970
10	U/S	460.50	33.21	"	13.8663	2.2746	0.8964	2.3881	0.1135
11	U/S	417.75	25.91	"	16.1231	2.6448	1.1430	2.6407	−0.0041
12	U/S	348.50	19.72	"	17.6724	2.8990	1.5097	3.0014	0.1024
13	U/S	311.75	16.00	"	19.4844	3.1962	1.8607	3.3524	0.1562
14	U/S	286.50	13.04	"	21.9709	3.6041	2.2831	3.7747	0.1706
15	U/S	274.00	11.35	"	24.1410	3.9601	2.6230	4.1147	0.1547
16	U/S	265.50	9.84	"	26.9817	4.4261	3.0255	4.5172	0.0311
17	U/S	254.10	8.93	"	28.4516	4.6677	3.3338	4.8255	0.1578
18	U/S	246.00	8.02	"	30.6733	5.0317	3.7121	5.2038	0.1721
19	U/S	243.00	6.94	"	35.0144	5.7438	4.2398	5.7815	0.0377
20	U/S	238.00	5.97	"	39.8660	6.5396	4.3869	6.4785	−0.0611

Equation of Regression Line V = 0.1696 N + 0.0029

TEST NO. TR4

Propeller No. 1 ; Pitch K = 0.1640′; Current Meter Depth = 9″ ; Water Depth = 1.46′; Meter Facing D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS. / SEC.	KN FT. / SEC.	TOW VEL. FT. / SEC.	$V_n = \lvert V_W + V_T \rvert$ FT. / SEC.	$V_n - KN$ FT. / SEC.
2[illegible]	D/S	56.10	-13.40	29.771	4.1866	0.6868	-2.2217	0.7300	0.0432
22	D/S	52.60	-13.40	"	3.9254	0.6439	-2.2217	0.7300	0.0861
23	D/S	88.00	-11.40	"	7.7193	1.2663	-2.6115	1.1198	-0.1465
24	D/S	76.65	-9.48	"	8.0854	1.3263	-3.1404	1.6487	0.3224
25	D/S	104.40	-8.46	"	12.3404	2.0243	-3.5190	2.0273	0.0030
26	D/S	115.20	-7.34	"	15.6948	2.5746	-4.0560	2.5643	-0.0103
27	D/S	121.60	-6.38	"	19.0596	3.1265	-4.6663	3.1746	0.0481
28	D/S	121.00	-5.55	"	21.8018	3.5764	-5.3641	3.3725	0.2961
29	D/S	127.10	-4.75	"	[illegible]	[illegible]	[illegible]	4.7753	0.3865
30	D/S	131.00	-4.13	"	[illegible]	[illegible]	[illegible]	5.7168	0.5136

Equation of Regression Line V = 0.1696 N + 0.0029

TEST NO. TR5

PROPELLER NO. 2 ; PITCH K = 0.3281′ ; CURRENT METER DEPTH = 9″ ; WATER DEPTH = 1.46′ ; METER FACING U/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	$V_n = \lvert V_w + V_T \rvert$ FT./SEC.	$V_m - KN$ FT./SEC.
1	U/S	556.00	104.70	29.771	5.3104	1.7422	0.2843	1.6381	-0.0441
2	U/S	264.40	36.81	"	7.1823	2.3565	0.8038	2.2226	-0.1339
3	U/S	176.80	19.76	"	8.9474	2.9355	1.5066	2.9204	-0.0151
4	U/S	149.00	13.36	"	11.1527	3.6590	2.2284	3.6422	-0.0168
5	U/S	136.00	10.22	"	13.3072	4.3658	2.9130	4.3268	-0.0390
6	U/S	124.00	7.83	"	15.8365	5.1956	3.8022	5.2160	0.0204
7	U/S	128.50	8.78	"	14.6355	4.8016	3.2918	4.8046	0.0030
8	U/S	141.88	11.87	"	11.9528	3.9215	2.5081	3.9219	0.0004
9	U/S	161.20	15.60	"	10.3333	3.3202	1.9084	3.3222	-0.0650
10	U/S	208.50	24.71	"	8.4379	2.7683	1.2048	2.6186	-0.1497
11	U/S	282.20	45.64	"	6.3355	2.0783	0.6523	2.0661	-0.0128
12	D/S	323.30	-85.45	"	3.7[illegible]	1.2413	-0.[illegible]	1.0654	-0.1759
13	D/S	104.00	-43.20	"	2.4074	0.7598	-0.6691	0.7247	-0.0651
14	D/S	21.66	-27.50	"	0.7876	0.2[illegible]	-1.[illegible]	0.3312	0.0723
15	D/S	32.00	-26.40	"	1.2121	0.3977	-1.1277	0.2861	-0.1116
16	D/S	251.25	-69.42	"	3.[illegible]	1.1874	-0.4289	0.9849	-0.2025
17	D/S	553.00	-144.40	"	3.8296	1.2564	-0.2062	1.2076	-0.0488
18	D/S	57.33	-69.60	"	0.8237	0.2702	-0.4277	0.9861	0.7158

EQUATION OF REGRESSION LINE $V = 0.3359\ N + 0.0020$

TEST NO. TR5

PROPELLER NO. 2 ; PITCH K = 0.3281' ; CURRENT METER DEPTH = 9" ; WATER DEPTH = 1.46' ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS./SEC.	KN FT./SEC.	TOW VEL. FT./SEC.	$V_n = \lvert V_w + V_T \rvert$ FT./SEC.	$V_n - KN$ FT./SEC.
19	D/S	19.00	- 16.40	29.771	1.1585	0.3801	[illegible]	0.4015	0.0214
20	D/S	21.67	- 15.10	"	1.4351	0.4709	[illegible]	0.5578	0.0870
21	D/S	25.50	- 13.60	"	1.8750	0.6152	-2.1890	0.7753	0.1601
22	D/S	44.90	- 11.40	"	[illegible]	1.2922	-2.6115	1.1977	-0.0045
23	D/S	46.00	- 9.50	"	4.8421	1.5886	-3.1338	1.7200	0.1314
24	D/S	41.25	- 8.90	"	4.6348	1.5206	-3.3451	1.9318	0.4107
25	D/S	56.00	- 7.45	"	7.5168	2.4661	-3.9961	2.5823	0.1162
26	D/S	60.00	- 6.22	"	9.6403	3.1648	-4.7863	3.3725	0.2077
27	D/S	62.60	- 5.58	"	11.2186	3.6806	-5.3353	3.9215	0.2409
28	D/S	67.80	- 4.88	"	[illegible]	[illegible]	[illegible]	4.6868	0.1286
29	D/S	71.67	- 4.28	"	16.7453	[illegible]	[illegible]	5.5420	0.0492
30	D/S	71.35	- 3.05	"	23.3934	[illegible]	[illegible]	8.3472	0.6722

EQUATION OF REGRESSION LINE $V = 0.3359\,N + 0.0020$

TEST NO. TR6

Propeller No. 4 ; Pitch k = 1.6404′; Current Meter Depth = 9″ ; Water Depth = 1.46′ ; Meter Facing U/S

Run No.	Direction of Tow.	Prop. Revs.	Time in Secs.	Distance	N Revs. / Sec.	KN Ft. / Sec.	Tow Vel. Ft. / Sec.	$V_n = \lvert V_W + V_T \rvert$ Ft. / Sec.	$V_n - KN$ Ft. / Sec.
1	U/S	102.10	94.75	29.771	1.0776	1.7677	0.3142	1.9144	0.1467
2	U/S	61.20	46.50	"	1.3161	2.1590	[illegible]	2.2405	0.0815
3	U/S	51.25	33.10	"	1.5483	2.5399	[illegible]	2.4997	-0.0402
4	U/S	36.80	22.55	"	1.6319	2.6770	[illegible]	2.9205	0.2434
5	U/S	34.65	18.95	"	1.8285	2.9995	[illegible]	3.1713	0.1713
6	U/S	32.10	15.00	"	2.1400	3.5105	[illegible]	3.5850	0.0745
7	U/S	30.50	13.80	"	[illegible]	3.6255	2.1573	3.7576	0.1321
8	U/S	28.65	11.78	"	2.4321	3.9896	[illegible]	4.1275	[illegible]
9	U/S	27.65	10.35	"	2.6715	4.3824	[illegible]	4.4767	0.0943
10	U/S	27.00	10.40	"	2.5962	4.2588	2.8626	4.4628	0.2040
11	U/S	25.90	8.90	"	2.9101	4.7738	3.3451	4.9453	0.1715
12	U/S	25.60	8.12	"	3.1527	5.1717	[illegible]	5.2666	0.0949
13	U/S	24.00	6.85	"	[illegible]	5.7474	4.3461	5.9464	0.1990
14	U/S	23.25	5.95	"	3.9076	6.4100	[illegible]	6.6038	0.1938
15	D/S	80.95	-107.40	"	0.7537	1.2364	-0.2772	1.3230	0.0866
16	D/S	39.80	-61.00	"	0.6525	1.0703	[illegible]	1.1122	0.0419
17	D/S	24.00	-43.30	"	0.5479	0.8989	-0.6727	0.9205	0.0216
18	D/S	8.60	-29.95	"	[illegible]	0.4710	[illegible]	0.6062	0.1352
19	D/S	6.57	-23.50	"	[illegible]	0.4586	[illegible]	0.3333	-0.1253

Equation of Regression Line $V = 1.6789\ N + 0.0189$

TEST NO. TR 6

PROPELLER No. 4 ; PITCH K = 1.6404′ ; CURRENT METER DEPTH = 9″ ; WATER DEPTH = 1.46′ ; METER FACING D/S

RUN NO.	DIRECTION OF TOW.	PROP. REVS.	TIME IN SECS.	DISTANCE	N REVS. / SEC.	KN FT. / SEC.	TOW VEL. FT. / SEC.	$V_n = \lvert V_w + V_T \rvert$ FT. / SEC.	V_n − KN FT. / SEC.
20	D/S	4.40	−15.30	29.771	0.2876	0.4718	−1.9458	0.3456	−0.1262
21	D/S	4.00	−13.35	"	0.2996	0.4915	−2.2300	0.6298	0.1383
22	D/S	7.35	−11.40	"	0.6447	1.0576	−2.6115	1.0112	−0.0464
23	D/S	8.68	− 9.71	"	0.8933	1.4664	−3.0660	1.4658	−0.0006
24	D/S	8.80	− 7.90	"	1.1139	1.8273	−3.7635	2.1682	0.3409
25	D/S	11.39	− 7.01	"	1.6248	2.6654	−4.2467	2.6467	−0.0187
26	D/S	12.19	− 6.02	"	2.0240	3.3217	−4.9453	3.3451	0.0234
27	D/S	12.18	− 5.99	"	2.0334	3.3356	−4.3701	3.3699	0.0343
28	D/S	12.45	− 5.52	"	2.2554	3.6998	−5.5933	3.7931	0.0933
29	D/S	13.62	− 4.80	"	2.8375	4.6547	−6.2023	4.6021	−0.0526
30	D/S	13.85	− 4.03	"	3.4367	5.6376	−7.3273	5.7871	0.1495

EQUATION OF REGRESSION LINE V = 1.6789 N + 0.0189